MOXLY'S THEORY OF THE TIDES,

BY

J. F. RUTHVEN.

THEORY OF THE TIDES.

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TIDES

WITH A CHAPTER OF EXTRACTS FROM MOXLY'S ORIGINAL WORK.

BY

J. F. RUTHVEN,

MASTER MARINER, LATE LIEUT. R.N.R., ASSOC. INST. N.A.,
YOUNGER BROTHER OF THE TRINITY HOUSE, F.R.G.S.
HONORARY CORRESPONDING MEMBER OF THE ROYAL GEOGRAPHICAL SOCIETY OF AUSTRALASIA.

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PREFACE.

FROM my earliest years as a navigator I always wanted to know the reason why, and Tides were the one subject in which I could never supplement practice with theory. Time after time I read the dynamical theory, only to throw it aside and console myself with the reflection that if I could make nothing of it, the great bulk of the tides were in the same predicament and refused to obey it.

If I sometimes wondered whether there could be anything wrong with the theory, I never ventured to say so, till I accidentally came across the account of Moxly's lecture at the Royal United Service Institution. At first, thinking that he was probably a "crank," I never took the trouble to read it, till one evening I had nothing else to do. The same night I wrote to the author, telling him that I endorsed his views, and felt for the first time in my life that I understood how tides were produced. Since then we have worked together to perfect the new theory, for it was hardly to be expected that every detail would be accurate in the first attempt on a subject which has puzzled some of the greatest mathematicians and astronomers. Going back to the fountain head, an original copy of Newton's *Principia*, we examined it and the works of later writers, with the result that I believe the theory now put forward will stand the test of time. In ten years not one of our contentions has been disproved, or even seriously disputed, so that although our views have not yet received the sanction of authority, I am so confident of their soundness that I feel it cannot be withheld indefinitely. Practical men see at once how such so-called anomalies as the one-day tides are (and have to be) produced, if our principles are admitted, and the navigator will, I believe, welcome a theory which accounts for actual tides, instead of making the majority of them irregular and mysterious.

The four short chapters here set forth are reproductions of articles which I published in the Australian and New Zealand Press. Appearing at intervals of over three months, each had to be more or less complete in itself, but the reiteration thus entailed will not be regretted if it makes the subject clearer. Perhaps, too, when thus administered in homœopathic doses, it will be more easily assimilated, and indicate the line of thought that we followed in the pursuit of truth.

J. F. R.

Dedication.

TO MY COLLEAGUE

THE LATE REV. J. H. S. MOXLY, B.A. (T.C.D.),

CHAPLAIN TO THE FORCES,

CHELSEA HOSPITAL.

PREFACE TO THE SECOND EDITION.

TO the original four chapters I have now added others read before the Royal Geographical Society of Australasia, and published in the *Nautical Magazine*, or the *Journal* of the Royal United Service Institution. In Moxly's account of the theory which he originated and we developed in collaboration, there was an error, due to accepting the assumption of the Dynamical theorists, that the only way the tangential component of tidal force could work was by means of surface currents. A closer examination showed us that it like the normal component produced pressure. He did not live to re-write his book from which I have added a chapter of quotations to supplement my account of our theory and emphasise points which I perhaps too briefly explained. In any case these extracts could hardly be improved upon.

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horse, whilst the fastest steed would want a good start to escape destruction from the awe-inspiring inrush to the Bay of Fundy, where the water rises from 50 to 100 feet, and transforms an enormous area of dry land into an anchorage that would float all the fleets of the world.

In other places we have only one high and one low water daily instead of two, and altogether at first sight the anomalies seem so numerous and chaotic as to hopelessly preclude the evolution of any system. But we know that Nature regulates everything methodically, and we see as we travel over the surface of the globe that land must interfere with the free working of any system, however perfect it may appear in theory. Exceptions will necessarily occur, but in face of two rival theories it is *prima facie* evidence in favour of one, if with few anomalies of its own (for most of which plausible reason can be given) it accounts for the numerous and inexplicable exceptions to the other, and shows that they are necessary results of the principles upon which it is founded.

Before the reader reaches the last page I hope he will agree that Newton's original theory was more nearly right than he supposed, when misled by the tidal streams of the Channel as Laplace was at Brest, and the inability of the moon approaching the meridian at Greenwich to carry the tidal cone with her across continents, he sought some modification that would make it more conformable to the few practical examples he had for comparison.

J. F. R.

MOXLY'S
THEORY OF THE TIDES.

"*Magna est veritas et prævalebit.*"

CHAPTER I.

In this chapter I have endeavoured to explain in popular language Moxly's new equilibrium theory of the tides, which is a reversion to the original theory of the greatest philosopher of all time, with a most important addition or correction, for want of which it was too hastily abandoned for the dynamical theory of Laplace—a system that the great bulk of the tides absolutely refuse to conform to. It is quite possible to predict tides from the analysis of a series of observations spread over a sufficiently long period of time, and this is still the only reliable method where land configuration is opposed to the free action of the tide wave. Most men, however, like to know how the forces of Nature work, especially in relation to phenomena that they are brought into frequent contact with, such, for instance, as the lengthening of the day as summer approaches. Whilst a much smaller number of people are affected by tides, the total is still considerable; and I hope that a simple explanation will interest many besides the tide predicter, to whom a true theory may prove a boon. It will, at least, help him to form a correct idea of the cause of the phenomena he is interested in; on the other hand, an erroneous theory can only be productive of confusion. Whilst I have purposely avoided using technical and mathematical terms, I hope that I have stated nothing that can be controverted by science or contradicted by Nature.

NEWTON'S EQUILIBRIUM THEORY.

The tides of the world have furnished a theme for speculation since the earliest times of which we have any record, and so many and fanciful were the theories advanced to explain their causation, that an ancient philosopher pronounced them "The Tomb of Human Curiosity."

When, at last, Sir Isaac Newton gave his equilibrium theory to the world, it seemed as if he had settled this question amongst many others in physical astronomy for ever. But Newton was apparently never quite satisfied that his solution of the problem was final, because he spoke of the tidal cone at different times as being under the moon, 90° behind her, and in an intermediate position. He seemed to feel that there was a missing link somewhere, and it is this missing link that I claim Moxly has discovered.

The original equilibrium theory may be illustrated by Fig. 1, taking S to represent the moon (or sun) and the circle a section of the earth, with T as its centre. If there was no disturbing force every particle in the circumference of the circle would be attracted equally by the earth's

gravity towards T. S also attracts every particle in the circle, but acts differentially. The attracting force at each point varies inversely as the square of its distance from S. Thus, if AS : PS : : 60 : 61, the attraction at A will be to that at P as the square of 61 is to the square of 60 or very nearly as 31 : 30. It will then be evident that the effect of the disturbing force of S in counteracting the earth's gravity is greatest at A and decreases as P and p are approached and passed, so that a rise in the water level at A is necessary to restore equilibrium of pressure. A is the summit of the tidal cone which slopes away gradually in every direction towards the regions of diminished interference with the normal force of terrestrial gravity.

Even with Bernouilli's modifications it was felt that Newton's theory was incomplete, and so the great French astronomer Laplace undertook the investigation of the problem. He threw overboard all of Newton's work which we believed to be sound, and substituted for it the dynamical theory, which has ever since been the received theory of the world, although its acceptance makes about three-quarters of the tides of the globe irregular or anomalous, and it is admittedly an "unsatisfactory explanation of the true condition of affairs."

The equilibrium theory places the tidal cone under the moon (for the lunar, or principal tide), where the level of the water is raised by her attraction, counteracting terrestrial gravity there more than on parts of the earth's surface at greater distances from our satellite. The apex of the tidal cone when unobstructed is only three or four feet above the mean level of the sea, and only five feet higher than the circle of greatest depression 6,000 miles away. For any tidal theory to work perfectly, the earth's surface should be covered completely with water of a uniform depth. If, in addition, we could stop the earth's rotation round its axis and the moon's revolution in her orbit, it is universally conceded that the equilibrium theory would require no supplementing. It is even admitted that if the moon then commenced to revolve slowly the equilibrium cone would follow her. In such a case, with an almost imperceptible progressive motion and such a long slope to the wave, the lightest skiff would rise and fall so gently even in mid-ocean as the wave crest passed under her that no movement would be apparent.

CONFUSION OF CURRENT WITH WAVE MOTION.

Then why was the equilibrium theory abandoned ? Because Newton was a man who always tried (and generally very successfully) to fit in all his theories with the phenomena he observed around him, and finding that in Nature most of the tides of which he had particulars made high water not when the moon was overhead, but perhaps, in or near the horizon, he naturally sought the cause. He saw the tides in the Channel rushing along the coast and up estuaries in rapid streams, which led to the idea that the tidal cone was produced by current, and so current and wave motion became inextricably confused by him and his successors. In the English and Bristol Channels the tide flows as a swift current *towards* the point of the compass that the unobstructed tidal wave should come *from*.

In current the particles of water are transferred laterally, but the swiftest current would take a long time to traverse one-quarter of the earth's circumference, which the tidal wave does along the equator in a

little over six hours. Wave motion, which is immeasurably more rapid, is undulatory only, and it is the form alone that moves laterally. It is like the waving of a flag in the wind, or a rope stretched tightly between two men, one of whom, if he moves his hand rapidly up and down, sends a swift undulatory wave along the rope, travelling nearly as fast as the eye can follow it.

Endeavouring to reconcile theory with observed particulars of tides that were really anomalous, the tidal theorists decided that, with the earth spinning and the moon revolving, as in Nature, currents have not time to produce the equilibrium form, so that in a prehistoric era the tidal crest fell back 90°, where, by the dynamical theory, it has remained ever since, dragged round in that position by the moon. They have, however, never explained satisfactorily how currents can do for the wave in that position what they were pronounced absolutely incapable of with the crest under the luminary. I believe, too, that currents which could produce such an astonishing effect would render the ocean quite unnavigable by the most powerful steamships in the world.

It is not suggested that Newton did not realise the difference between wave motion and current, but merely that in trying to reconcile his theory with the tides which came under his observation it did not occur to him that these latter were caused by local conditions and obstructions in the shape of land to the free working of the beautiful system he had evolved. Considering the magnitude of his unrivalled work, it is not astonishing that Newton occasionally made a slip, but that he made so few.

WHY LAPLACE SUBSTITUTED THE DYNAMICAL THEORY.

Newton, also by an oversight, applied the same theory to the tidal problem as to the orbital motion of a planet, failing to observe that once a particle becomes part of a solid or flexible ring the conditions are no longer the same as when it was alone in an orbit. In the latter case it is alternately accelerated and retarded by a disturbing force in the four quadrants of the orbit, but in the ring, whenever the accelerating force is applied, the same force is retarding the corresponding particle in the adjacent quadrant, and so the only result will be pressure between the two points, whose tendency is to compress and alter the shape of the ring.

The line P S represents an accelerating force, and the line p S a retarding force of equal magnitude, acting on the ring as it revolves round T in the

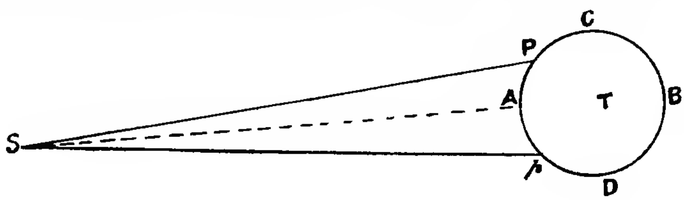


FIG. 1.

direction C A D B. It must be obvious that they neutralise each other, and so the ring is neither accelerated nor retarded. Their tendency (and effect if they are strong enough) is to make A approach S.

It must also be evident that every other particle in the quadrant, C A, which can be subjected to an accelerative pull from S has a corresponding

particle in A D receiving a retarding pull of the same magnitude. Each pair may be compared to an equally strained pair of drag ropes on a wheel, of which T represents the axle.

It is a similar pressure applied to innumerable particles on each side of the spot under the moon (the pressure increasing as the distance from the spot increases) that creates the tidal cone, or would do so on an ideal tidal world. Where it does not act thus in Nature is the effect of shallowing sea floors and land getting in the way to obstruct the progress of the tidal wave.

It was upon this oversight of Newton's that Laplace founded his dynamical theory, many of the results of which are absolutely contradicted by Nature even in the open ocean, where theory ought to be seen at its best. Laplace went to Brest to study tides, and it was probably the strength of the tidal stream there that finally convinced him that the problem was a dynamical one. He saw the water surface so raised by obstructions to the tidal wave that a strong current was produced to restore the level in the immediate neighbourhood.

The number of anomalous tides is enormously reduced if we revert to Newton's equilibrium theory with Moxly's modification. Under the dynamical theory tide tables are largely a dictionary of tides that will not conform to it (for which no reasons can be given), many of which can be shown to be necessary results of the theory that I have tried to explain in simple language, avoiding technicalities as much as possible.

ATMOSPHERIC TIDE CONFIRMS EQUILIBRIUM THEORY.

In looking for confirmation of this theory, which I have never doubted from the first, I discovered in Grant's *History of Physical Astronomy* an account of an atmospheric tide. The observations were taken on the island of St. Helena about 70 years ago, and their analysis showed conclusively that the tidal cone was under the moon, as we contend that it always would be on the surface of the ocean, were it not for continents acting the part of obstructing breakwaters across the path of the tidal wave, and the friction caused by the bottom in shoal water. In the case of the atmosphere, there are no similar obstructions.

The solar tide, although smaller, is governed by laws precisely similar to those for the lunar tide, and it is a simple operation for the tidal expert to combine the effects of the two.

MOXLY SUPPORTED BY NATURE.

I hope I have made it clear that what currents admittedly cannot find time to do, pressure can and actually does accomplish. Reduction of the force of gravity under the moon as she moves over the earth's surface will be instantaneous. The response in the shape of an elevation of the water level will be equally so, although the rise will be gradual because the differential attraction of the moon changes gradually, and the tidal wave has more than six hours to rise 5 feet.

Nature's processes are always simple when we understand them. Could anything be simpler than this : Get rid of the idea of impossible currents, such as no navigator has ever encountered, and yet would be an every-day experience if the dynamical theory were true ; substitute the differential pressure of gravity due to the moon's attraction ; and the only difficulty becomes to imagine any other result than the gradual and gentle rise of the tide as we observe it in Nature.

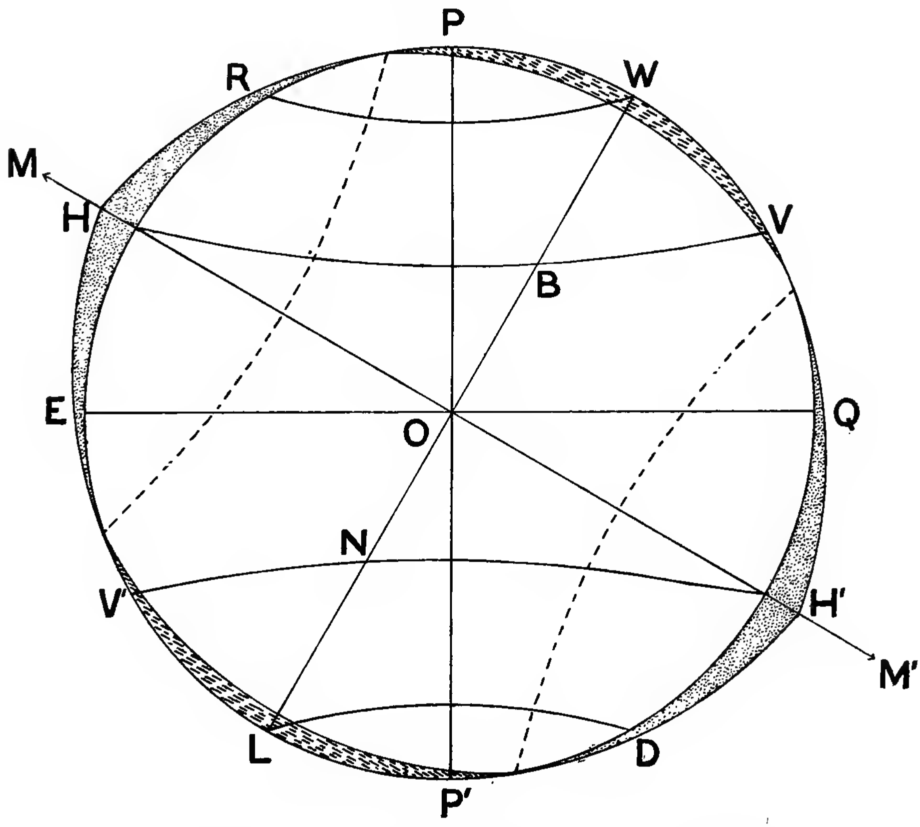
Pressure is the missing link, and I believe that it completes the theory of Sir Isaac Newton, and closes for ever the "tomb" mentioned by the old Greek philosopher.

EXAMPLES OF TIDES

which cannot be explained by the dynamical theory, and are a necessary result of the new equilibrium theory :—

In the accompanying diagram P and P′ represent the poles of the earth, and the line joining these points the axis on which it rotates. E Q represents the equator, and the prolongation of H′ H past M the momentary

DIAGRAM I.



The elevations and depressions are, of course, purposely exaggerated.

direction of the moon when she has extreme northern declination. Now, by the dynamical theory, the tidal cone will be at O, whether the moon is as represented or has no declination, *i.e.*, when she is over the equator. By the equilibrium theory the tidal cone is as shown in the figure under the moon at H, and will follow her as she moves south to E, and continue to do so when she crosses the equator. At right angles to the direction of the moon in the figure, the line L W represents the centre of a belt of low water, the dotted lines indicating the circles of mean level.

At places on the coast of British North America we are informed by the tide tables that diurnal inequality is so great as to produce only one

high and one low water in 24 hours, but no tidal expert before Moxly could show any reason for the phenomenon. The explanation is quite simple. It never occurs when the moon is on the equator and the tidal cone at E, but when she is as shown in the diagram, a place on the parallel of 61° north latitude will have its lowest water when at W. As the earth rotates on P P′ the place will be carried in 12 hours to R, where it has its highest water. The tide will not be so high as at H, but it will he higher than anywhere else on that parallel, and 12 hours later it will be back at W and find low water.

Here is a quotation from the Tide Tables concerning the tides of the east coast of Australia generally, and Sydney Harbour in particular, which is quite inexplicable by the dynamical, and that is as simple as the summer sun giving longer daylight by the new theory :—

"From April to October the night tides are higher than the day tides, and the reverse for the rest of the year. The usual sequence of the tides is from the lower low water to the higher high water."

"In June and July the night tides are at times nearly 2 feet higher than the day tides, and the reverse in December and January. It is stated that the highest tides occur with westerly winds."

A reference to the diagram will make the reason clear.

Take the simplest case of spring tides at full and change of the moon in the height of the southern summer, when the sun will be near the parallel of H′, which may be taken to represent Sydney. At full moon she will be somewhere in the direction of M, when the sun is crossing the meridian of Sydney, and the anti-lunar tide will combine with the solar direct tide to make the highest possible high water. Whilst this is happening during the summer day at Sydney, it is night and winter at H, where the anti-solar is helping the lunar tide to give the greatest rise in the 24 hours. But H, the apex of the night tide, is far from V′ near which Sydney will be 12 hours after having passed near H′. There must, therefore, be a difference in the height of Sydney's two tides, the daylight tide (at H′) being the higher and the night tide (at V′) the lower. Of course, it is evident that when Sydney is at H′, where the sun is, and where it is in or near the apex of the tide, its tide will be higher than when it is at V′, which is far from the apex, and it is equally clear that the lower tide (V′) will be at night.

At new moon she will be approximately over Sydney between the earth and the sun, with the same result as before, except that it is the lunar and solar tides that are now working together, whilst the anti-solar conspires with the anti-lunar tide during the winter night in the northern hemisphere. Where, however, the tide has to make its way as a current up a long channel or over a shallow sea, the time of high water at a place will be delayed, and in such cases the tide which was originally a day tide may not arrive till night, and the tide which is properly a night tide may not arrive till day. Day and night tides are thus interchanged in Burrard Inlet.

But for such exceptions the rule holds good all over the world. Day tides are higher than night tides in summer. In winter night tides are the highest. The effect of the westerly winds I will explain later.

Again, we find the sequence of high and low waters on the Pacific coast of North America spoken of as anomalous, and a footnote inserted detailing observed facts which they cannot explain. They can be shown to be a

necessary consequence of Moxly's theory. By it the lowest L.W. will be when the moon has swept across the Pacific and reached the eastern shores of Asia, because there is no land between it and the west coast of America to interfere with its action. As the moon crosses the continent of Asia the anti-lunar tide, or lower of the two high waters, will take place. By the time the moon reaches the meridian of the Azores it will again be low water, but this time the moon's action takes place over the continent of America, across which it cannot draw the water, and so, as stated in the Tide Tables, "there is a slight fall (sometimes merely indicated by a long stand)." As the moon crosses the American continent its tidal force gathers freedom of action, and by the time it reaches the coast of California there is no obstruction to its attracting the waters of the Pacific Ocean and forming the highest high water. Again, it must be obvious that the effect will be greater when the moon has high declination than when she is on the equator.

Thus, if Moxly's theory be accepted, these tides can be shown to be the natural result of known causes, instead of being so complicated and anomalous as to require an "explanation," which only states observed facts without any explanation whatever of the cause.

For similar reasons, on the western side of a large ocean where the tidal wave has free scope, it will be found that the effect of obstructing land upon diurnal inequality will be to make the highest H.W. follow instead of precede the lowest L.W., as the above quotation from the Admiralty Tide Tables states is actually the case on the east coast of Australia. I could easily multiply examples like the foregoing, and generally speaking, wherever the tidal wave has a free sweep, the so-called anomalous tides can be explained by the new theory. At Hong-Kong, for instance, the night tides are higher in winter, and the day tides in summer, as in Sydney, and for the same reason. But where land interferes with the system, the most we can hope for is by careful observation to discover how the anomalies are produced.

DYNAMICAL PITFALLS.

As an example of the pitfalls the dynamical theory may lead to, Laplace, after prolonged mathematical investigation, asserted that there could be no diurnal difference where the sea was of fairly equable depth. But in the Pacific, where the depth is more uniform than in other seas, the greatest diurnal differences were subsequently found. He said that diurnal difference could be great only about the 45th parallel, and that it should vanish towards the poles. But in the Pacific, where in any case, according to him, the difference should be small, the diurnal inequality was so great that about the 60th parallel it caused one of the daily tides to disappear, and as I have already explained there is only one high and one low water in the day. On an ideal world for tidal theory (one completely covered with water to an uniform depth) this must happen every month between 60° and the pole. Whilst adjacent latitudes will exhibit practically the same phenomenon, the parallel that is the same distance from the pole as the moon from the equator is the one to produce it exactly. Nature and Moxly both contradict the great French astronomer's assertion of maximum inequality in Lat. 45°. Now, Laplace was a very great mathematician, and the only reasonable hypothesis to account for his conclusions being so wide of the truth, is that he started with false premises.

THE DISPUTED COROLLARIES.

But in case the reader should think differently, I will now furnish him with material to form his own opinion, by transcribing a translation of the corollaries and our criticisms of them. The diagram is Newton's original figure for Prop. 66, Book I., of the *Principia*, with the addition of one line, which was not required for the proposition itself, but is necessary for a just appreciation of the corollaries. Of course P may be at any point in the circle or orbit, but a ring must pass through all the points.

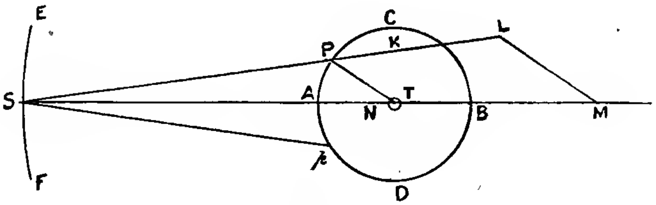


Fig. 2.

In the diagram, if P represented a particle or a planet, revolving in its orbit in the direction C A D B, the attraction of S would accelerate its motion through the quadrant C A, and retard it from A to D. In the corollaries Newton applies the same principles to tidal theory. He says :—

Cor. 18.—" Let us suppose that under the same laws by which the body P revolves about the body T many fluid bodies are revolving about T at equal distances from it. Let us suppose that these bodies are so numerous that they all come into contact with one another, so as to form a fluid annulus, or ring, concentric with the body T ; if the several parts of this ring move under the same laws as the body P, they will draw nearer to the body T, and move more swiftly in conjunctions and oppositions of the body S than in quadratures."

In Cor. 19, Newton continues :—" Let us suppose now that the spherical body T is enlarged so as to extend itself on every side till it reaches the fluid ring. Let it have a canal containing water cut all round its circumference. Suppose this enlarged sphere to revolve uniformly about its axis. The water in the canal, being accelerated and retarded alternately, as in the last corollary, will move more swiftly at the syzygies and more slowly at the quadratures than the surface of the sphere, and so will ebb and flow in its channel as the sea does."

Newton seems here to have overlooked a most important consideration, the neglect of which appears to vitiate the whole argument of the corollaries, and to be responsible for the misconception of the mode of tide generation, out of which so many inexplicable anomalies have arisen.

THEIR MISAPPLICATION.

The statement in Cor. 18 that if the several parts of the fluid ring move under the same laws as the separate body P, they will draw nearer the body T, and move more swiftly in conjunctions and oppositions of the body S than in quadratures, appears to be incorrect, inasmuch as it ignores the fact that while the forces and the laws by which they act are the same, the conditions are very different in the two cases, and the results will therefore be very different. The separate body P, while it occupies the

position given in the diagram, is subjected to an accelerating force, and in obeying the impulse of that force its motion becomes swifter, and when it shall have reached the position marked *p* in the diagram it will be under a retarding force, in obeying which it will move more slowly; but the separate body P is never being acted on by an accelerating force at the same time that it is being acted on by a retarding force. On the other hand, when the separate body is replaced by a ring, the ring being one body is subjected to an accelerating impulse at P, and at the same time to a retarding pull at *p*. As the forces so applied are equal in intensity, and opposite in direction (with respect to rotation of the ring) the sole result of their action upon the ring will be to draw, or press, the parts between P and *p* together, that is, to cause a pressure amongst the particles composing the ring towards A, the point in which the opposite pulls meet. There cannot possibly be any tendency as the result of the simultaneous pulls at P and *p* towards accelerating the rotation of the ring, and as little can there be retardation. There can be no alteration of the velocity of rotation, but only an alteration in the shape of the ring, which will be made to bulge towards A. The free body P has now become a particle in the cross section of the ring of water, and the whole cross-section is being drawn towards the point A. At the same time the similar cross section of the ring at the point *p* is being drawn by an equal force towards the same point A, and a body of water lies between the two cross sections so drawn together.

Water cannot flow in any direction unless there is a space into which it may enter. In this case there is no space into which the water may flow, and the necessary consequence of the pressures from P and *p* would seem to be a rise in the level at A till the protuberance of water produced equilibrium of pressure. This seems an irresistible conclusion, because there is no room for an incompressible fluid in any other direction. It is the way we contend the tangential component of the attractive force acts, and not by inducing currents. At A the vertical component of the attractive force is also counteracting gravity, necessitating a corresponding rise in the water level, and thus the whole attraction of S will be engaged in generating the tidal protuberance, and not the integrated horizontal component only, as by the dynamical current theory.

Currents require indefinite time, or have to travel at impossible rates, but the response to pressure is instantaneous, and the tidal cone under its influence will be kept under the moon (when unobstructed) just as a sensitive barometer responds to atmospheric changes, and as iron filings fly to a magnet.

ANALOGOUS PARALLELS.

Moxly gives as an example of the instantaneous result of pressure, the case of a long tube filled with incompressible peas. If another pea be forced in at the near end, one will drop out at the other extremity at the same instant. Pressure and motion will have been instantaneously transmitted throughout the whole length of the tube, no matter how great that length may be, but the motion is not that of a current any more than is the movement of the mercury in the cistern of a barometer, and the time required is infinitesimal.

Another pertinent illustration may be obtained from the behaviour of a soft iron sphere, when rotated on an east and west axis. It has no

permanent magnetism of its own, but under the influence of the parent magnet the earth, is a magnet by induction, its poles being in the line that a freely-poised dipping needle would come to rest in, *i.e.*, in the line of the meridian, and horizontal if on the magnetic equator. Now, it is well known to experts in magnetism that however fast the globe be rotated, or rolled along the earth in a north and south direction, the poles will preserve their relative position to those of the dominating magnet, the earth. As the globe rolls forward, the poles shift backward in obedience to the inexorable laws of magnetism. We believe that the attraction of gravity, or, rather, the effect of any variation in it, is as instantaneous as that of magnetism, and that no time is required for an unobstructed tidal cone to respond to it.

Again, imagine an indiarubber globe of two or three inches diameter securely fixed near the end of a light steel rod representing its axis. If pressure be applied to the imaginary equator by the finger and thumb, it will contract the diameter between them and slightly elongate that at right angles to it. By a turn of the wrist the contracted and elongated diameters can be made to rotate rapidly, and yet no particle of the globe moves more than an infinitesimally small distance. Thus it is with the water of the ocean under the differential pressure of the tide-producing luminary, and there is no necessity to bring water by surface currents from great distances to produce equilibrium.

CONCLUSION.

It is difficult to upset a doctrine emanating from such a source as the one I have referred to, especially after its passing for more than two centuries unchallenged. Nevertheless, I believe that it is only because of the great name of the author that it has never been questioned before, and I have little fear of our statements being disproved. It is with a full sense of the responsibility incurred, and a profound veneration for the memory of the greatest master of science that the world has ever seen, that we submit our conclusions for unbiassed judgment. Newton's reputation is so transcendent that fifty such oversights would not affect it any more than a bucketful of water would reduce the level of the ocean. His work is not to be measured by such a false standard as whether he was right or wrong on any particular point. To estimate it at its true value, we must compare the state of knowledge and science at his advent upon the scene, when he took his degree at Cambridge, in 1665, with that when the *Principia* appeared in 1686, and when, in 1696, after a severe illness, he resigned the Lucasian chair to take up a sinecure at the Mint and practically to retire from the arena, for although a little later he was elected president of the Royal Society, his work was done. That the progress in this short period was almost entirely due to his unequalled intellect, was testified to by all his contemporaries, both British and foreign. The Italian Lagrange, the greatest mathematician of the eighteenth century, the great French astronomer Laplace, and the perhaps equally famous German Gauss, all united in placing Newton on a special pedestal high above all others.

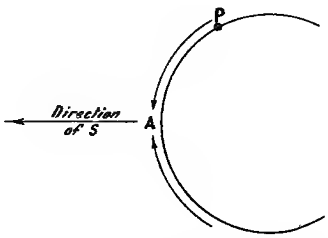
CHAPTER II.

In the previous chapter, with a view to simplifying the problem for a larger number of people, I dealt only with the lunar tide, which I showed was due to the differential attraction of the moon on the half of the earth presented to her, causing pressure to raise a cone of water vertically under our satellite when land configuration does not obstruct its formation. No tidal theory, however, would be complete that did not explain the elevation of water on the opposite side of the earth to the tide-raising body, called in the case of the moon the anti-lunar tide, which it will be the object of the present chapter to describe.

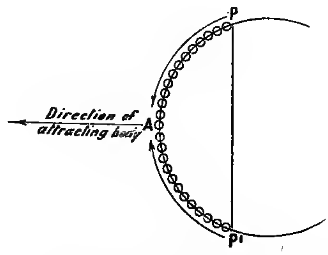
First, however, I would like to state that I have been told that it is only the dynamical wave that travels at the velocity I indicated, and that the currents which make the wave move at a much slower speed. Now, if we assume these latter to travel at even one-fiftieth of the pace

Diagram II.

To illustrate the difference between the effect of attraction on a particle revolving in its orbit, and on a similar particle in Newton's canal or ring round the earth's surface. The equilibrium tide may be conceived as composed of an infinite number of such canals all converging to the point A under the moon.



Particle revolving in orbit and free to answer to forces alternately accelerating and retarding velocity.



Particles in canal on surface of rotating sphere. An infinite number of rows of particles are being attracted towards A from P, and from the direction of P a similar number are being attracted. Consequently a block is established at A. The resulting pressure causes the surface to rise.

of the wave, they would still amount to 20 nautical miles per hour (33·78 feet per second) on the equator, and 13 in the English Channel. Where is the navigator who has ever seen or heard of such currents? With the tidal cones in quadrature they would run to the eastward and to the westward simultaneously from underneath the moon, reversing their motions at each place as she came on the meridian. Their intersection by similar currents from the direction of the pole (which, like the trade wind, rotation would deflect to the westward) would create such vortices as have never been observed since the mythical days of Charybdis, and such chaos in Dead Reckoning as no mariner could unravel.

By the corrected equilibrium theory there would be no current whatever due to tide on the ideal world assumed by Laplace, and practically none even on our globe in the open ocean, except where land interferes with the free action of the tidal cones. Whatever may have been Newton's original idea of tide generation, no later writer on the subject before Moxly has ever suggested pressure, but all speak of wave and current motion as the only means by which the tidal protuberance can be formed, and an approximation to equilibrium produced.

ANTI-LUNAR TIDE.

Before explaining the formation of the anti-lunar tide, it is necessary to make sure that the reader understands what is meant by the common centre of gravity about which the earth and moon revolve, and centrifugal force. If two round shot of different sizes be joined together by a very thin but rigid bar, and this latter balanced horizontally on a vertical pivot, the point of application is the common centre of gravity of the system. If now the size of the larger sphere be increased sufficiently, there will be no point in the bar which will produce horizontality. The centre of gravity will have retreated to a position beneath the surface of the larger sphere, but still in the line joining its centre to that of the smaller globe. If we substitute the invisible tie of mutual attraction for the bar, the foregoing illustration is a sufficiently near approximation to the case of the earth and the moon, where the common centre of gravity round which they both revolve is buried 1,000 miles beneath the earth's surface, because our globe is more than eighty times heavier than her satellite. But the rod acted both ways, whilst mutual attraction only keeps them from separating, and it is at once evident that there must be another force preventing them from coming together. This exact balance to their mutual attraction is centrifugal force, which is the cause of the anti-lunar tide. If a weight be whirled round at the end of a string the strain on the operator's hand will be a practical illustration of centrifugal force counteracting the centripetal force that keeps the weight captive. The greater the velocity of the weight, the greater the centrifugal force, as will be indicated if the string be elastic, by its stretching, and if the speed be increased sufficiently by its breaking. If a bucket full of water be whirled round fast enough not a drop need be spilt, centrifugal force counteracting terrestrial gravity. Should the bucket be weak and the velocity great, the water might even leave in opposition to gravity, taking the bottom of the bucket with it.

The total attraction of the earth and moon on each other may be supposed to be concentrated in their centres, and exactly balances the centrifugal force of each generated by their revolution about their common centre of gravity, but as explained in the previous chapter, the attraction of the moon on each particle of the earth varies inversely as the square of its distance from the luminary. The near side of the earth is 59 times her radius from the moon, the centre 60 radii, and the far side 61 radii distant. Consequently her attraction on particles situated in the positions named varies as the inverse squares of these numbers, and the attraction on the centre may be taken as the mean, or average, attraction. These "overbalances," as they are called, are admittedly the tide generating forces, one raising the water by diminishing terrestrial gravity (thus

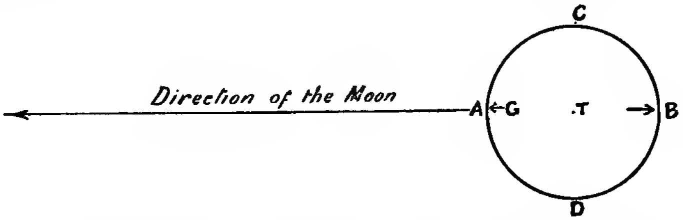
increasing the centripetal force or attraction of the moon), the other by the centrifugal force of revolution, the overbalance of which throws the water out into a cone.

PARTING OF THE WAYS.

Up to this point the theories are fairly in agreement, but now I come to the dividing line. By the equilibrium theory the tidal cones remain on an ideal world under and opposite the moon, where the generating forces are most favourably placed for their production ; by the dynamical theory the cones are in quadrature, where the "overbalances" are a minimum, if they do not actually disappear. The following diagram will make this clear :—

DIAGRAM III. TIDE GENERATING FORCES.

As the moon is 60 times C T distant, the points C, D, and T are all practically the same distance from her.



The circle C A D B represents the earth. G is the common centre of gravity of the earth-moon system. The small arrows represent the overbalances. At A centripetal force overbalances centrifugal force. At B centrifugal force is the stronger.

It will be evident that if the attraction on the earth's centre is the average attraction, the moon's influence will be greatest at A and least at B, but at C and D, owing to the great distance of the moon, it will be as nearly as possible the same as at the centre, *i.e.*, as the average. Now the centrifugal force, unlike the centripetal, is the same at all these points, and so at C and D the tide generating forces disappear.

Moreover, it is admitted that at C and D the moon's attraction is wholly engaged assisting terrestrial gravity to lower the level of the water there, and that at C the tangential component of this force, which by the dynamical theory drags the tidal cone round after the moon, is *nil* (*vide* Herschell's *Outlines*, p. 465).

BAROMETER CONFIRMS THEORY.

It has long been known that the height of the barometer affects the tide, and that a difference of 1 inch of mercury will have a marked effect on the depth of water. Taking the Admiralty Tide Tables estimate of 20 inches of water for a difference of 1 inch of barometric pressure, it is conceivable that the fall of the barometer in a cyclone might cause a rise in the water surface that would counteract, or even more than counteract, the depression below the usual level between the two tidal cones in the open ocean. This well-authenticated effect of barometrical fluctuations is strong confirmation of the assumption that the lunar tide is caused by pressure, when the maximum lateral movement in the water could not

exceed the vertical rise of 7 inches per hour. It would be an abuse of language to call this a current, even though the cone or wave form keeps pace with the moon. Whether such a wave would conform to the trochoidal theory of deep-sea waves is more an interesting speculation for the theorist and mathematician, than material to my argument that it would cause no embarrassment to the navigator.

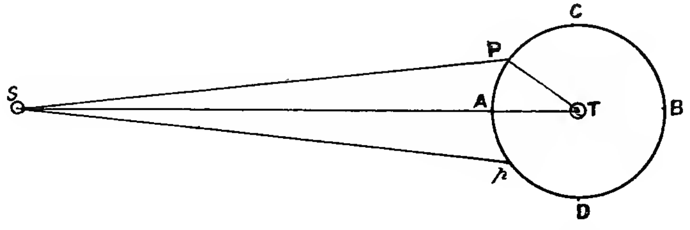
ROTATION CONFOUNDED WITH REVOLUTION.

Just as in the dynamical text-books, tide is indifferently spoken of as wave and current, so also rotation seems to be confused with revolution. Now revolution produces tide-generating force, whereas rotation cannot do so, although it brings successive meridians into the already formed cones, which would travel round the globe once in a lunation if the earth were fixed on its axis.

If the earth were fluid, or had a deep and uniform coating of water all over it, and rotating in space without any disturbing body near it, the greater centrifugal force near the equator would cause a rise in the water level there and a corresponding depression near the poles, but the protuberance extending right round the earth, would be in no sense tidal. There would be no rise and fall of water, yet in an orthodox work on the tides we read of currents running from where the moon is in the horizon to where she is in the zenith, as if rotation was a tide generator. If there was no attracting body, rotation would produce an equatorial protuberance ; if rotation was stopped, the moon revolving would produce two tides in the lunar month ; she would be once near the zenith, once near the nadir, would rise and set once. Rotation, whilst it is a non-generator, carries the different meridians in turn through the protuberances formed by revolution. As the earth and moon revolve in about* 29½ days, each meridian will pass under the moon about 28½ times, and there will be 57 tides in a lunation.

Even in the corollaries which I criticised revolution is changed into rotation and treated as if they were synonymous, as I will now show :—

FIG. 3.



P is first described as a particle revolving in an orbit, but the moment that T is enlarged till it fills the circle C A D B, P becomes merely a particle on the surface of a rotating sphere. On this corollary Laplace based his theory, so that he made tide depend upon rotation, and I have shown that rotation is not a tide-generating force.

* The moon makes a sidereal revolution in 27·322 days, during which time the sun will apparently have advanced 26·93°. It will take her another 2·21 days to revolve through 29·1° and complete the lunar month, or synodical period of 29½ days.

CONCLUSION.

A friendly critic, who left Cambridge as a wrangler, recently told us that no person (in the mathematical world) now believed in Newton's ring, and added, " So why do you lay so much stress upon that ? " Our reply was to the effect that his statement was only another reason for getting rid of a theory based upon a fallacy. If the foundation is unsound the edifice does not deserve to stand, however eminent the architect, and I have a shrewd suspicion that owing to the deservedly great reputation of Laplace as a mathematician, later authorities have been more intent on adding to his structure than examining its foundation.

Later still I have noticed in a Cambridge text-book that the 18th and 19th Corollaries are omitted, and also the 20th Corollary, in which Newton puts the tidal cones about octant. All three corollaries are in the copy in the British Museum, but the last was ignored as far back as when Sir George Airy wrote on the subject.

If, as stated, the dynamical track is beset with pitfalls, the path of the reformer is hardly strewn with roses. It is a thankless task exposing errors (or what one thinks are errors) that have been persisted in so long as to be looked upon as hardly less than gospel truth. In drawing attention to them, however, I disclaim all intention of depreciating the work of others, or casting any reflection on the abilities of living writers, who only expound the theory handed down to them by Laplace, who again, because of misleading and insufficient data, based his mathematical reasoning on false premises. Such, at least, is our belief, which only disproof will shake. Had he and Newton had the tidal data now available, especially that of the great Southern Ocean, where alone on our globe the tide wave gets a fairly unobstructed sweep, the dynamical theory might never have been heard of. I have the less scruple in condemning it, in that I believe that the substitute I propose is the theory originally evolved by Newton, which he only modified after comparison with the tides about the British Islands, and west coast of Europe, where of all localities on the watery portion of the earth's surface the moon has perhaps the least chance of producing a true tidal cone, and can at best by her differential attraction only press up some of the water of the Atlantic to meet her on its eastern border. As a navigator I would like to see the tidal problem put on the simplest and surest foundation, by reviving what I believe to be the original statical theory of the great Newton, whose transcendent ability was only surpassed by his modesty, when he described himself as " only like a boy playing on the seashore, and diverting myself in now and then finding a smoother pebble, or a prettier shell than ordinary, whilst the great ocean of truth lay all undiscovered before me."

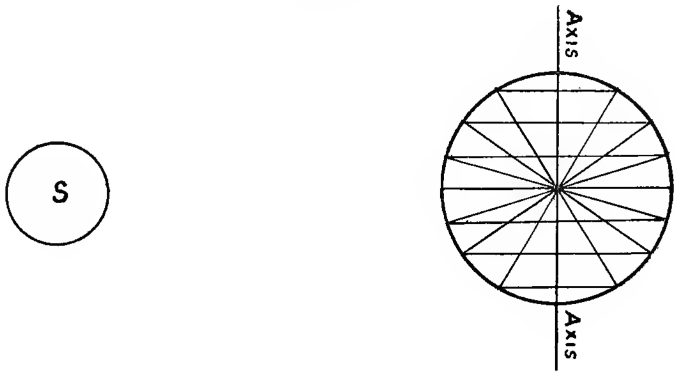
CHAPTER III.

In two previous chapters I explained and illustrated by diagrams the formation of the lunar and anti-lunar tides by the over-balances of the centripetal force or attraction of the moon, and the centrifugal force of revolution, the over-balances being caused by the fact that whilst the centrifugal force of every particle of the earth is the same, the centripetal force varies inversely as the square of the distance from the moon, being stronger than its rival on the side next our satellite and weaker on the opposite side, whilst it must be exactly equal to it on the average, because she continues in the same orbit year after year. I showed that whilst this was probably Newton's original conception of tide generation, he modified it and framed his corollaries to represent Nature as he observed it, and I ventured the opinion that had he known that in the great Southern Ocean the tide crest when unobstructed is under the moon, the dynamical theory would never have been heard of. I showed that Laplace, studying Nature in the same limited field of observation, went one better than Newton, abandoned all idea of compromise, and based his dynamical theory on the corollaries, which we have since demonstrated are unsound and untenable. This latter fact has now been admitted by one of our most distinguished opponents, who, hard pressed in his defence of the dynamical theory, has thrown Newton overboard, and told us that modern tidal theory is not based on the great master's work at all, forgetting or ignoring the fact that ten years ago his colleagues quoted these corollaries as in themselves sufficient refutation of Moxly's contentions. The professor went on to object that the new theory was not expressed in mathematical language, and that quantities were not specified. But here again he ignores that there is nothing quantitative about the 66th Prop. and its corollaries, and that our dispute is not about "quantities," but "principles." We are not at present concerned with the height of the tide (be it one foot or one mile), but the principles which govern its generation. The professors cannot have it both ways. Either the dynamical theory is based on the corollaries or it is not. We believe that it is; but whether or not, we can show conclusively that Newton's original oversight in them has run right through the explanation of every later writer on the subject, each of whom has either confused rotation with revolution, or substituted one for the other; and such a pitfall has this proved that the dynamical theorists of to-day exhibit grave and even vital differences in their presentation of the theory, differences which are sufficient to shake the faith of any man capable of thinking for himself, the centrifugal force of rotation having a very different origin and effect from that of revolution.

By a lapse, to which even the greatest intellects are liable, Newton failed to observe that his enlarged T (in Cor. 19) was merely a rotating body, with P as a particle on its surface, and that the force developed by rotation was centrifugal only from its own axis, acting equally in all directions. As its effect in raising the water level would be constantly the same at all places situated on the same parallel of latitude, it could

not be a tide-raiser. As it is directed as much towards as from S, it would be absolutely incapable of counteracting the gravitational attraction of S, with which T would inevitably collide under the assumed conditions. The only force capable of preventing the catastrophe would be the centrifugal force of revolution of S and T round their common centre of gravity, which is left out of the problem. This force would be a perfect balance, but it is not even alluded to, and we are left with a rotating T, which may be taken to represent the earth, subjected to the attraction of S representing either the sun or the moon, with no force to prevent them coming together. Newton apparently never looked backwards, or he would probably have seen and corrected the result of his inadvertence; but this initial error (exchanging revolution for rotation) escaped observation, and has, we believe, consciously or unconsciously, misled all his successors from Laplace onwards. By altering the perspective, and drawing the diagram on the plane of a meridian, instead of that of the equator, the

DIAGRAM IV.



effect of gravity and the centrifugal force of rotation can be better seen. If the right hand figure represents the earth, the radial lines show the direction of gravity from all points on the surface towards the centre; the parallel lines exhibit the direction (and relative magnitude) of the centrifugal force of rotation at right angles to the axis, and how, whilst it decreases from a maximum at the equator to zero at the poles, it is the same for every place on the same parallel of latitude. A glance at the figure, however, must make it obvious that whatever the strength of the centrifugal force of rotation, it can have no effect in counteracting the attraction of S, which is thus left unbalanced. Such conditions could not continue in Nature.

DYNAMICAL PROFESSORS DISAGREE.

I will now give briefly the cause of tide on dynamical principles, according to three different modern professors, two of whom have been prolific writers and lecturers, and whilst I only use initials, I can give chapter and verse for every quotation or deduction :—

Professor B attributes tide to—

1. Rotation of the earth on its axis.
2. Rotation of the moon on its axis.
3. Orbital revolution.

Professor D gives as the cause of tides the overbalances of—

1. The moon's attraction or centripetal force.
2. The centrifugal force of revolution of the earth round the common centre of gravity of the earth-moon system.

Professor P says: "Any particle of the fluid is acted on by the following forces—

1. The attraction on the particle of the whole mass, including the sea.
2. The differential attraction of the sun and moon.
3. The force arising from the surrounding fluid, which, in a perfect fluid, as water very nearly is, we may regard as a normal pressure (termed by mathematical physicists p) per unit of surface acted on.

From these, now, mathematicians proceed without assumption by the laws of motion and principle of continuity."

When placed thus side by side, the most casual observer cannot fail to be struck with the many and varied interpretations that the dynamical theory receives (indicative of an insecure foundation), and he will probably agree that it is time to reconsider a theory that makes such widely different impressions upon three of its highly-trained and able exponents, besides being contradicted at every turn by Nature.

The first two were the latest popular explanations before the world immediately preceding Moxly's advent, and the third seems to have been evolved to take the place of the discredited corollaries. It, like the first, I hope to show, could not account for tides as we know them. The second is all-sufficient if allowed fair play, but the author, misinterpreting his own statements, substitutes, as he proceeds, rotation for revolution, and dynamical currents for differential pressure. This ignoring of what he had proved, and abandonment of the principles he had so well enunciated, leads him to admit that his theory is no more to be trusted than the original equilibrium theory, and that both must be abandoned as "satisfactory explanations of the true condition of affairs." With that conclusion we are absolutely in agreement. The fundamental error of mixing up rotation and revolution is as fatal to one as to the other.

ROTATION *versus* REVOLUTION.

If the earth, originally spherical and covered uniformly with a deep coating of water, were the only body in space, the effect of rotation would be to generate centrifugal force from its axis, which would be a maximum at the equator, and decrease gradually to zero at the poles. This would undoubtedly alter the shape of our planet, as the force generated by rotation acting against the earth's gravity would cause an elevation of water in the equatorial regions and a flattening at the poles. In fact, the earth would become what it is—an oblate spheroid, but this change of shape would in no sense resemble the alternate rise and fall that we call tidal.

If the earth and the moon were the only pair of bodies in existence, and deprived of rotation, they would revolve round their common centre of gravity, separated by a distance determined by their original rectilinear velocities and their masses. The distance would be such that the centrifugal force of revolution would exactly balance their mutual

attraction upon one another. Whilst it is obvious that on the whole these two forces are equal and oppositely directed, they differ, in that whilst the centrifugal force of every particle in the earth is the same, the attraction varies inversely as the square of its distance from the centre of the moon. This being so, attraction being greater on the side next the moon, will cause the water level to rise there; on the remote side of the earth, centrifugal force will be the stronger, and the water will be thrown out *en masse* into a cone, corresponding to that raised by attraction on the other side.

If now, while the rotation of the earth is still in abeyance, we suppose that the moon goes round the earth once in a month, these two tidal cones will travel with her, maintaining their relative places. Granting Newton's laws of motion and gravity, these two tides must result, and these two only. They account for all there is to be got, not only out of the centrifugal force of revolution, but also out of the moon's differential attraction, so that (these forces being fully expended and incapable of doing work over again) when we take the next step towards actuality and start the earth rotating, no more tides will be raised. The permanent equatorial bulge before described will result, and the tides in each place will appear more frequently. Instead of having to wait a fortnight for the next high water, rotation will bring it round in about 12½ hours (12 in the case of the solar tide), not by raising the water in your locality, but by carrying your meridian to where the other tidal cone is.

As this point is the crux of the whole difference between us and the dynamical people, I will endeavour to drive it home by analogy. Imagine a circular dock with two travelling cranes placed opposite one another at the sides, and suppose each crane exerting its full power to have raised one ton weight above the level of the quay wall. Let the cranes be made to travel round still facing one another, or, better still, let them be supposed to remain stationary, and the quay wall to rotate under them, so that each portion of it passes under the weights in turn. Would anybody say that a ton weight had been lifted opposite each point? Surely not. No more lifting power was available after the two single tons had been raised, but every point in the rotating quay wall has passed under them in turn. So it is with the earth; and if it took to rotating in 12 hours the number of tides would be doubled, whilst no more water would be raised except the slight addition to the height of the cones due to the greater centrifugal force, which would lengthen the equatorial diameter and increase the overbalances.

If rotation has thus no tide-raising effect on the rotating body, it still more obviously has no effect of this nature on the other body. The earth's rotation raises no tide on the moon. The moon's rotation, slow as it is, has neither more nor less effect on the tides of the earth than when, in centuries gone by, she rotated faster. Her sole effect is that of attraction, which depends only on her mass and the square of her distance. Her gravitational effect may be supposed to be concentrated in her centre, which is a point having no magnitude, and independent altogether of rotation.

I have now disposed of two of Professor B's tide-raisers. The third, of course, produces, as with us, the anti-lunar tide, but leaves his explanation altogether incomplete and defective.

Professor P, on the other hand, includes in his list of forces or principles,

" differential attraction," which will account for the lunar tide, but his other two, " the attraction of the earth upon its own particles," and the pressure " p," rather resist than cause the elevation of tide. The centrifugal force of revolution, without which the earth and the moon would assuredly come together, is not even mentioned, and so he only accounts for the lunar, as Professor B only for the anti-lunar, tide.

We have to thank Professor D for the most lucid account extant in popular language of the " tide-generating forces " and " over-balances," up to the point where he introduces rotation, which, he says, makes " no difference." I have already explained that the difference it makes is shortening the intervals of time between the high waters that it has had no hand in raising, but the Professor—following the precedent of the corollaries and all Newton's successors—makes the grave difference of mixing up its effects with those of revolution. He shows clearly when explaining the action of tide-generating force from the circle of moonrise and moonset, towards where she is overhead and underfoot, by the short intervals of time he mentions, that he is thinking and talking of the apparent diurnal motion of the moon due to the earth's rotation, and not to the effect of revolution. He introduces currents which we believe do not exist, except where created by obstruction to the true theory, and he explains on dynamical principles how the wave gets left a quadrant behind the moon, a position that we maintain it never would occupy, except again through obstruction, and he illustrates this by the analogy of forced oscillations of a pendulum. But here, again, the Professor is not happy. Granting, for the sake of argument, that the pendulum is a good and true analogy, if it proves anything, it is that the wave crest cannot be where he says it is. The interference with the pendulum inverts it, but the interference he claims for the tide wave, only semi-inverts it. A complete inversion, as with the pendulum, would simply exchange the lunar tide for the anti-lunar ; each would move round a semi-circle, whereas he states, and is trying to show, that the tide wave goes back only a quadrant.

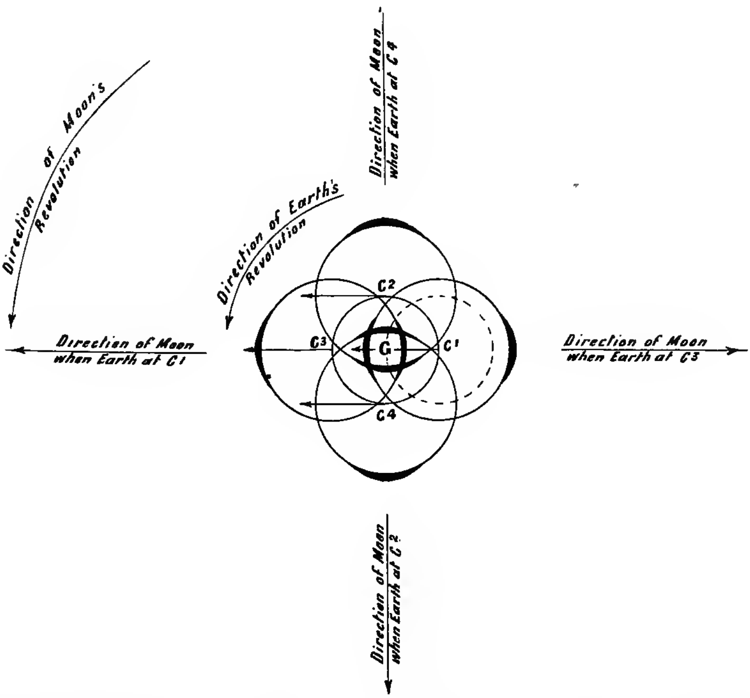
But we dispute that there is any analogy between the motion of a tide wave on an ideal world (or even on our own globe when unobstructed), which is continuous in the same direction, and that of a pendulum which moves alternately to and fro. If the mathematical critic objects that I am disputing the well-established principle of forced vibrations, I reply that such is not the case, and that I only contend and show that it does not apply in the tidal problem. Its aid was only sought to explain what the few tides observed up to Laplace's time seemed to assert. Those tides, not then known to be anomalous, suggested what was not true, for the normal tide wave. Any explanation based upon them was bound to be contradicted by Nature sooner or later, and feeling that she had already asserted her prerogative and refuted it, we sought, and, I believe, found, the weak spot that necessarily existed in a theory, which was supposed to support the explanation.

INTERACTION BETWEEN EARTH AND MOON.

The earth and moon revolve round their common centre of gravity once in a lunation, during which time the former rotates about 29 times, whilst the moon makes but one turn round her axis, always keeping the

same face towards us. These motions, taken together, are rather complicated, and so it is usual in explaining the tides to consider the case in the first instance, as if while the two bodies were revolving, the earth was deprived of rotation, introducing this latter movement when the effects of revolution have been fully considered and allowed for. I have followed this plan, and also for similar reasons assumed the moon to be over the equator, as after we have mastered the simple case, variations of declination can be allowed for, high declination accounting for some of the so-called anomalies. In my short illustration of revolution (in former chapter) I simply substituted for the thin and rigid bar with which I started, centripetal and centrifugal forces, which, whilst near enough to explain what followed, is not the whole truth. As the moon moves round the non-rotating earth, and their common centre of gravity must lie in the line joining their centres, it necessarily follows that this centre of gravity, which we will call G, is not a fixed point, but describes a circle round the earth's centre about

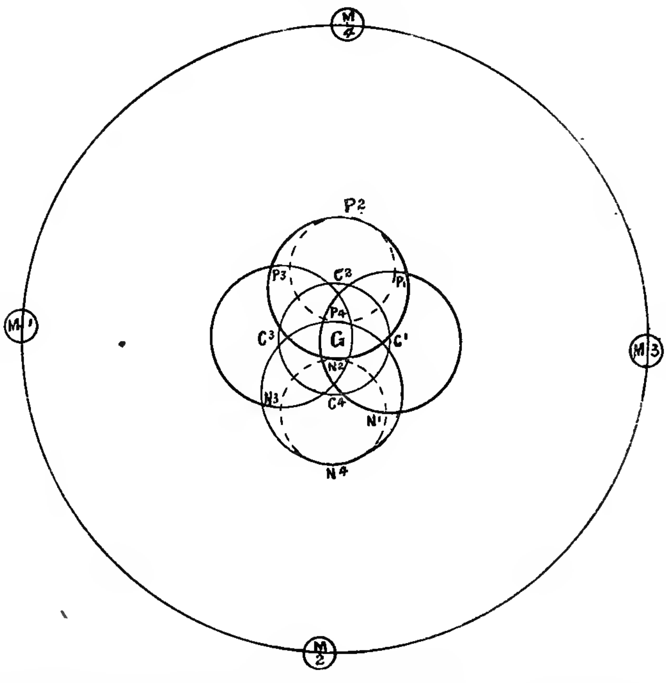
Diagram V.



1,000 miles beneath the surface. Whilst the moon at the long end of the imaginary lever describes her monthly orbit, the non-rotating earth at the short end would describe hers with a radius less than her own, and the motion would be very similar to that of a disc of sandstone in the hand of a seaman operating upon a stain in a deck plank. If he is facing north, the fingers will point approximately in that direction during the whole of each turn, and if the hand could be made to work with machine-like regularity, so that the centre of the disc described a circle round the central

point of the stain, each and every point would also describe a circle of the same radius, but no two circles would have the same centre. The actual points, however, having the same average distance from the moon, and describing circles of equal radii, would have the same centrifugal force, but the only one going round G as centre is the centre of the earth. Diagrams V. and VI. are an attempt to illustrate this movement. When the moon is in the direction of C1, the earth will be represented by the right-hand circle, with the tidal cones marked on it, the arrow projecting through the lunar crest, showing not only the rise of water, but also a typical line of particles, which preserve the same direction throughout the revolution. G is the position of the common centre of gravity of the system, and the

DIAGRAM VI.



dotted circle its path round the earth's centre. As the moon proceeds towards the direction C2, the non-rotating earth would move to the position of the upper circle, the arrow keeping horizontal, and G moving (relatively) down and to the right, remaining always on the line joining the centres of the two bodies. The tide crest following the moon, the water would fall on the arrow shaft till when the earth reaches C2, the surface would be half as much below mean level as it had been above it. As the moon proceeds towards direction C3, the water will again rise on the arrow shaft, and the remaining quadrants will be completed in the same manner, the earth's centre describing the circle C1, C2, C3, C4, with G as centre and radius G C. Every other point will describe a circle of the same size, but each with a different centre.

A reference to Diagram VI. will make it clear that the points P and N will describe the circles P1, P2, P3, P4, and N1, N2, N3, N4, of the same

radius, one being wholly above, and the other below G, but as each and every particle describes a circle of equal radius in the same time, they will all develop the same centrifugal force.

REPLY TO CHALLENGE.

Moxly was recently challenged by a University professor to prove his "dictum" that revolution has and rotation has not tide-raising force. As his reply may appeal to some readers better than my explanation, I will give it in his own words. After reminding his correspondent that the dictum is also Professor D's, he continues :—"At least, it is his dictum when he is explaining the phenomenon of the tides, even though he forgets it when he passes on from the explanation. It is mine, too, with this difference, that I never forget it. But let us see what will happen when the moon revolves about the earth in a day (the earth being non-rotating and neglecting the sun's revolution). When the moon revolves round the earth in a day the earth must also revolve in a day round G, the common centre of gravity of the system. There will be over-balances of centrifugal force and attraction, only greater than now, for the moon and earth will be nearer to one another, and greater tides than ours will be raised, and if the earth be non-rotating they will simply revolve with the moon round the earth once in a day. Anyone living on the earth in such conditions will experience two tides a day as we do. Now, let us give the earth rotation, and first let it rotate in the time the moon revolves in. The earth will then always keep the same face towards the moon ; the protuberances of water will always preserve the same position on the earth, and will be as little noticed as the equatorial bulge, some 13 miles in height, is noticed by us. What has caused the tides of the non-rotating earth to disappear when it rotates ? Plainly the rotation. Has, then, rotation lowered the tides ? Surely not. The tides have not been lowered. The protuberances of water have not been lowered. They exist as before, but as they are now permanently in the same position, their presence is not felt. Let us, however, suppose the velocity of rotation doubled—What happens ? The tides reappear as formerly when there was no rotation, twice a day. We have the tides disappearing through rotation, and reappearing again owing to still more rotation. Does not that prove my dictum over again ? If it be untrue, as it surely must be, to say that in the first case rotation lowered the tides, it is equally untrue to say that in the second case rotation raised them. That paragraph of yours afforded me the means of bringing out the truth of my dictum more clearly. And that is so as to every objection brought against my view and principles up to the present. I venture to suggest that this is not the case with a false theory."

CONCLUSION.

As long as Newton's laws of motion hold, revolution of a body about a point must be accompanied by the development of centrifugal force. So long as the law of gravity stands, differential attraction of one body upon another must exist, and I believe I have shown conclusively what I think no mathematician would deny, that upon these grounds alone tide upon the ideal world becomes a necessity. These forces, if the earth were

non-rotating, would cause two lunar tides in the month, high waters occurring at full and change of the moon.

Rotation also develops centrifugal force, but I hope I have made it abundantly clear that the resulting protuberance is not tidal. Its *rôle* is simply to bring the water of the different meridians in turn into the positions where the over-balances are always elevating or depressing the surface, and would do so even if we could suspend axial rotation.

The undisputed tide-raising forces only account for one tide each out of 57 in a lunation, so that if we assumed the other 55 to be raised by the centrifugal force of rotation this force would be enormously greater than that of revolution, which is manifestly absurd, and proves, if proof were necessary, that quantities must give precedence to principles.

I have endeavoured to explain what we hold to be the true principles of tide generation altogether apart from quantitive values, which only become useful when we know how and in what directions the forces act. The navigator could never find his port if only given a distance or a speed, whilst kept in the dark as to its bearing or the course to steer. In this case, as with the tides, quantitive value alone might only lead away from and not towards the desired goal.

CHAPTER IV.

In the foregoing pages I have endeavoured to formulate the motion of the tidal cones on an ideal world if allowed perfect freedom to pursue their courses unobstructedly. But we know that not only does our globe not answer to this description, but that there are several other interferences which alter or modify the time and depth of high water at any particular place, such as wind and barometrical fluctuations. These, however, are not part of the true theory, but hindrances to it, which have nevertheless to be taken into account when dealing with actual tides. The influence of land may be estimated more or less approximately in advance, but as we never know long beforehand what the height of the barometer will be, or the direction of the wind, their effects cannot be foretold for more than a day.

The effect of large tracts of visible land in obstructing and even arresting the progress of the tidal cones is too obvious to require more than a passing remark. The action of the invisible land at the bottom of the sea is not so evident, but is equally certain, even though less in degree and more variable in amount, according to the angle of slope of the bottom as it rises to meet the dry land. This angle is not only an ever-varying one along any particular parallel, but may also differ considerably from those along adjacent parallels, and as angular slope and reduction of the depth of water cause friction and retard the free progress of the tidal cones, the tide is delayed and current produced. This current is then the product of the forces which would cause no current on the ideal world of Laplace, and the local conditions under which the same forces have to work on this far from ideal tidal world of ours, and is not really anomalous because it is explicable, and might be predictable if we had sufficiently accurate measurements of depth all over the globe, and if they were not so mixed up with other obstructions. At present it would often be like trying to forecast the speed of a 15-knot ship up a river with a swift and variable current against her—a current depending upon the amount of melting snow and other unknown quantities, which might vary from hour to hour. The ship would not be any the less a 15-knot vessel if it was found that she had only averaged 12 knots up the river.

Again, wherever the partial tidal wave passes a promontory like the Cape of Good Hope, the land beyond which has arrested the passage of the remainder of the cone, a derived tide, in the shape of a free wave, must result to restore the difference in level. Now, whilst it has been explained that the tidal cones produced by the over-balances must travel as forced waves at the same rate as their generators, it is quite different with a free wave, whose speed is regulated by the depth of water. A tide of this nature from the South Atlantic, combining with the true tidal wave in the North Atlantic, is doubtless responsible for the enormous rise in the Bay of Fundy.

The retarding effect of bottom friction can be best observed in shallow water. It can be seen daily on any seabeach, and is most marked when an on-shore gale magnifies the ripples and waves into a dangerous surf.

If the effect has been noted by fewer observers in deep water, it is none the less authentic, and is the stereotyped explanation of the dangerous sea in the Bay of Biscay in a heavy westerly gale, where, as the Atlantic waves meet the shallowing sea floor, their length gets shortened by friction, and there is a tendency for each crest to overtake those in front, and so crowd a series of them together. But, perhaps, the best example is seen off the Cape of Good Hope when beating to the westward against winter gales. Experienced navigators will remember that the effect is so marked on the edge of the Agulhas bank as to be a warning for a ship standing off shore to put about and avoid damage from the sea, which now threatens to sweep the decks. Either on the bank, or well clear of it, the sea runs true with a natural wave-length and velocity proportioned to the depth of water, but as the waves from an ocean two or three miles deep approach comparatively shallow water, the steep edge of the bank acts like a powerful friction brake in retarding their speed, producing a short and hollow sea that is trying to the very finest and best-found ships, and has caused some of the weaker ones to founder.

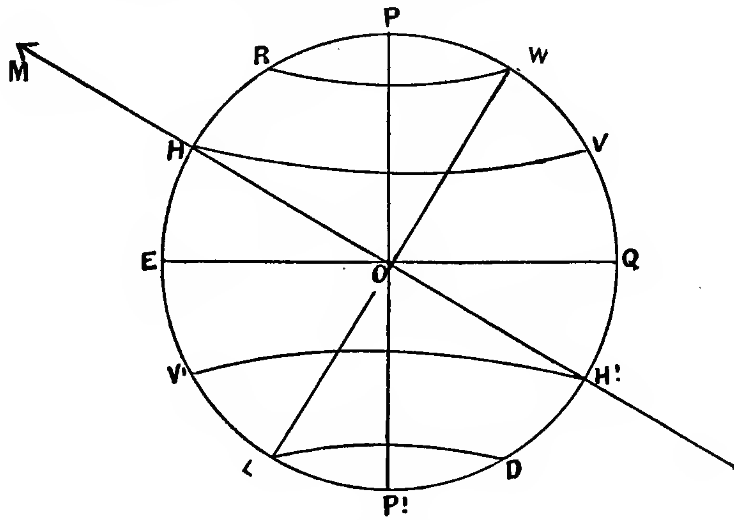
I will now give an example from the tides of the world, showing how these illustrations apply and confirm our theoretical conclusions. The summit of the tidal cone never reaches the latitude of New Zealand, but the slope of its southern shoulder sweeps across that region of the earth with a freedom denied it elsewhere. As it approaches the islands they stretch for over 700 miles, like a great breakwater across its path, and retardation results all along the coast. At no single point on the east coast of New Zealand is it high water at full and change until after the luminaries have passed. As we get near the extreme south, however, we notice that the retardation is comparatively small, and at the south point of Stewart Island it is *nil*. High water occurs exactly where we say it should, *i.e.*, under the moon. As the tidal wave passes on to the westward, the island of Kerguelen is too small to create much retardation till it is actually reached, and so the tide arrives with the moon on its east coast. Retardation at once commences, and it is not till two hours later that high water reaches Christmas Harbour on its N.W. side.

A westerly wind nearly all over the world seems to increase the depth at high water; and check the ebb tide, whilst an easterly wind has the opposite effect. Wind creates surface friction, even when the water is absolutely smooth, and as ripples are produced which give place to waves, the effect increases and a surface current is set up. It is obvious that when the wind is westerly both friction and current will act against the progress of the tidal cone, and have a tendency to retard it and bank the water up. Then, again, a westerly wind is generally accompanied by a low barometer, and we know that a fall in the mercury always means a rise in the water level. On the other hand, an easterly wind is almost invariably associated with a high barometer, and they work together to reduce the tides generated by the overbalances, which may be in some cases completely masked by these interferences. In Albany, Western Australia, for instance, the tides seem to depend very largely upon wind and barometer, besides being complicated by diurnal inequality in a way that is altogether inexplicable by the dynamical, but a necessary result of the equilibrium, theory. Winds from polar or equatorial regions cross the path of the tide wave at right angles, and so neither tend to accelerate nor to retard it. Nevertheless, they often have a very appreciable effect,

where they blow on to, or off a coast, into or out of a harbour, or estuary. For instance, the tidal wave arrives off the S.E. point of Australia with the moon, whence, though retarded, it travels along the south coast. As it passes Port Phillip entrance the level is raised comparatively to the surface inside, and the water rushes through between the heads in a rapid stream. On the principles I have enunciated, it is obvious that a westerly wind, by raising the level, and a southerly wind by increasing the velocity, will accentuate this effect, and tend to pen the water in the bay when the tide has ceased to flow. On the other hand, an easterly wind, by reducing the level, and a northerly wind by accelerating the ebb stream and blowing the water out of the bay, will have the reverse effect. These deductions from our theory, working under local conditions, are amply confirmed by observation of the tides of Port Phillip, where a strong S.W. wind may keep the water from falling materially while it lasts, and a fresh N.E. wind will prevent any rise much above mean level. These effects so often manifest themselves before their causes that the tides are nearly as reliable as the barometer in predicting the weather.

I have now briefly enumerated the principal and perhaps all the sources of interference with the pure theory that would govern the tides on an ideal world, as regularly as day and night succeed each other. On our

DIAGRAM VII. TO EXPLAIN DIURNAL INEQUALITY.



Let E P Q P′ be the meridian under the moon, P and P′ the poles and the line joining them the earth's axis, E Q the equator, and M the direction of the moon with extreme declination, say 29° N, when L W will be the circle of lowest water.

When the moon is over the equator in the direction Q E produced the tidal cones will by the equilibrium theory be at E and Q, and by the dynamical theory at O and the corresponding point on the far side of the earth. In either case there will be no diurnal inequality. When the moon moves to M, the cones will by the dynamical theory remain at O and its opposite point, and there seems no reason why one should produce a higher tide than the other at any given point. But by the equilibrium theory they will be at H and H′. As the earth rotates on P P′, the water at the place that was at H will fall until when it crosses L W, the tide will be the lowest possible. As it approaches V, the water will again rise, but at V, being 58° away from H′ the tide will be much lower than it was at H. On parallels between H V and the equator the diurnal difference will be less, and on the polar side of H V it will increase, till at R W in 61° N. latitude there will be but one high and one low water in the lunar day.

world the problem is much more complex, but not beyond the wit of man to unravel, if in watching the tides and the movements of the luminaries he also notes all that may modify their action. Land configuration, atmospheric pressure, and wind, all play their parts, as do also the positions of the sun and moon, both in their orbits and in declination, and also the latitude of the observer. When the sun and moon are nearest the earth they naturally create greater over-balances and larger tides, as I think is admitted by everybody. On the other hand, declination has never received credit for its full effect by the dynamical theorists, which is presumably due to the fact that if the crest of the tidal wave was, as they assert, 90° behind the moon, it would travel round the equator whether she was on the celestial equator, or 30° north or south of it, *i.e.*, altogether independent of declination. A glance at the diagram will make this clear, and so it is difficult to conceive how by the received theory there can be any diurnal inequality. But diurnal inequality, which is simply the difference between the heights of the lunar and anti-lunar tide at any place, has in opposition to Laplace's theory, been found to be almost universal, and to culminate in single day tides, where, according to him, it should be disappearing. Observation has connected its increase with the movement of the moon away from the equator. The supporters of the received theory have noted this fact, and being unable to account for it on dynamical principles, fall back on the equilibrium diagram to explain these "diurnal declinational tides," whilst proclaiming that the diagram represents nothing in Nature.

Their misconception of the equilibrium theory and effect of declination is well exemplified in their estimate of the ratio of the sun's tidal force to that of the moon, by comparing spring tides with neaps. We are told that the lunar equilibrium tide is double the solar tide, and that therefore spring tides should be three times greater than neaps. They tell us again that "though the tidal force of the sun is in theory the same in all places, it is found by observation to be different in different places," and again, "this difference appears in the different ratio of the rise of spring tides to the rise of neap tides. In general, the rise of spring tides above mean water is about double that of neap tide, which gives the solar tide *one-third* that of the lunar tide. But in some cases, the spring tide exceeds the neap tide only by one-third, which gives the solar tide only *one-seventh* of the lunar tide." In another place, we read that the sun's force is but *one-seventeenth* that of the moon.

These extraordinary discrepancies, which no supporter of the dynamical theory can explain, are necessary results of the new equilibrium theory, where the position of the tide-producing luminaries with respect to one another, and to the latitude of the place, are allowed for. This can be best shown by an example which I take from Moxly :—

"Suppose the place on the 50th parallel of latitude, and let the time be about equinox. At *Full Moon* the place will be 50° away from the summit of the joint tide cones of the sun and moon, and the high water will not be considerable. At *Neap*, in a year of great declination, the moon will be within some 20° of the zenith of the place, while the sun remains still near the equator. This neap tide being so near the apex of the moon's tide will be at the place very large for a neap tide. Again, let the time be at solstice. At *Full Moon* the place will be, perhaps, some 21° or 22° only away from the apex of the joint tide, while at neap the moon will

be over the equator, and therefore 50° away from the place. The neap tide will consequently be a small one. In the latter case, the ratio of the spring tide to the neap would be great ; in the former case the neap would not be much less than the spring. Can anything be more absurd than the attempt to calculate the ratio of the sun's tidal force to that of the moon, by comparing spring tide and neap tide together, at a place on the 50th parallel at either of the times specified ? "

With the aid of the *Nautical Almanac* the navigator can always see at a glance the interval between the meridian passages of the sun and moon, and how many degrees each will culminate from his zenith, and so apply these principles to his locality. Then, with due allowance for the interferences I have specified, he will find the tides as amenable to natural law as other phenomena.

Although the moon's appearance in the horizon is not the signal for currents to commence or change direction, her presence is often so important to the navigator that it will not perhaps be inappropriate if I conclude with some short rules for finding the time of her rising and setting. Based upon Napier's *Analogies*, they combine the merits of brevity and accuracy, and are independent of all special tables.

When rising and setting the altitude is *nil*, and the zenith distance a quadrant. Consequently her hour angle can be quickly found by quadrantal spherics :

$$\text{Cos. } P = -\overset{+}{\text{tan. }l}.\ \overset{+}{\overline{\text{cot. }p}}.$$

P being the hour angle, l the latitude, and p the polar distance.

In quadrantal spherics, when two sides of a triangle come together, a — sign is prefixed besides the signs over them, according to whether they are more or less than 90°. The product of the three signs gives the sign of the cosine, and indicates whether the hour angle is more or less than six hours. When the moon is rising P is the easterly hour angle, and has to be taken from 24 hours to get the westerly hour angle.

From the above we readily deduce the following rules, which obviate the necessity of using the signs :—

If the latitude and declination are of the same name, take the arc or time less than six hours corresponding to the cosine, and add 12 hours to it, to get the westerly hour angle ; if contrary names, take the time less than six hours, and subtract it from 24 hours, to get the westerly hour angle.

Then, MEAN TIME AT PLACE = P + moon's R.A. — M.S.R.A.

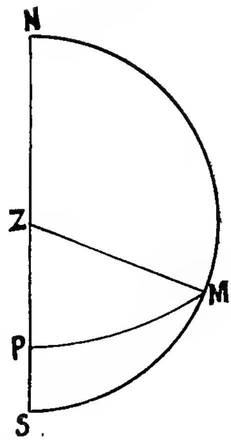
The moon's R.A. and Dec. can be taken out at sight for the nearest hour from the *Nautical Almanac*, and the M.S.R.A., or sidereal time, from Page II. of the month.

For the time of setting proceed as above, but without subtracting from 24 hours, as P found with its appropriate declination (which, owing to the moon's rapid motion, will differ from that at rising) is the westerly hour angle, *i.e.*, take the time corresponding to the cosine, and if the same name, subtract it from 12 hours.

EXAMPLE.

Find the time of moonrise at Sydney Heads July 16th, 1908.— Estimating it to be about 8 p.m., which is 10 a.m. G.M.T., we take out the elements from the *Almanac* for that hour :—

Fig 4.



$$\text{Then } \cos. P. = \overset{+}{-} \tan. l. \overset{+}{\cot}. p.$$

l. 33° 50′	tan.	9.82626	
p. 74 7	cot.	9.45415	
5h. 16m.	cos.	9.28041	

	12		
☽ 's W Hour ∠	17	16	
,, R.A.	22	9½	
Mer. ,, ,,	15	25½	
M.S.R.A.	7	35½	
M.T.P.	7	50	P.M.
		— 5	
Standard Time	7	45	P.M. of Moonrise Sydney Heads.

If apparent time at place is desired, use the sun's right ascension instead of that of the mean sun. In practice the logarithms need only be taken out to four places of decimals.

CHAPTER V.

Before Sir Isaac Newton revolutionized Physical Science there was no tidal theory worthy of the name. Then, in a comparatively few years we had two, the equilibrium and the dynamical theories. The former was originally, as its name implies, wholly statical, but it was leavened with dynamics before being displaced by the theory of Laplace, which of course was mainly, if not wholly, dynamical.

Dealing for the sake of simplicity with the lunar tides only, the apices of the cones are, by the equilibrium theory, at the extremities of that diameter of the earth which is directed to the moon ; whilst the dynamical theory places them on an equatorial diameter at right angles to this, or in quadrature. A moment's reflection will show that in the first case they will move north and south as the moon changes her declination, and that in the second they must travel round the equator whether the moon is over it or the 28th parallel of latitude.

The equilibrium theory was finally abandoned because in Great Britain and Northern Europe the moon is often in or near the horizon, instead of on the meridian, when it is high water, and it was assumed that surface current was the only means of producing equilibrium, which the actual rates of revolution and rotation made impossible of attainment. In the transition stage it was altered to agree better with tides round our coasts ; rotation got mixed up with revolution and current with wave motion. Now, rotation, as I will presently show, has a very different effect from that of revolution, and current bears only a superficial resemblance to wave motion. In current the movement of the particles is approximately horizontal, whilst in wave motion it is principally, if not wholly, vertical.

Laplace continued to treat rotation and revolution as if their effects were identical. He retained the currents as necessary to the formation of the dynamical wave, and supposed that a small vertical rise entailed an enormous horizontal movement. If the equilibrium theory did not agree with the tides of the Channel, the dynamical theory has utterly failed to account for the numberless tides observed in all parts of the globe since Laplace's day, even in the open ocean, where conditions are most like those of the ideal world that he assumed, and the predictions of a sound theory should be verified by approximation to actuality.

The admitted discrepancies between theory and observation, and the numerous anomalies, seem to suggest a reconsideration of the whole subject, which is equally interesting to the mathematician and the navigator. Following on the lines of my late colleague Moxly, I will now endeavour to show that on the ideal world of Laplace (one completely and uniformly covered with a deep coating of water) the tide-raising forces would produce no currents, which on our world are due to obstruction to the free passage of the tidal wave ; that rotation raises no tide ; that all true tide is due to differences of pressure ; and that the dynamical theory is untenable.

1. A homogeneous fluid sphere hanging alone in space would attract all particles on its surface equally towards its centre; *i.e.*, all particles would be of equal weight.

2. On such a sphere set rotating equably (*i.e.*, with uniform angular velocity) about an axis there would be formed a protuberant band or bulge in the equatorial regions and an area of depression or flattening about the poles: the sphere would be altered in shape and become an oblate spheroid. The fluid in the equatorial regions, having greater centrifugal force, would rise to form the protuberance, and that nearer the poles would be depressed till the effect of the counteraction of the gravity of the sphere by the greater centrifugal force of the equatorial regions was compensated for by the weight of the elevated water, and the pressure from surface to centre again equal on all sides. The amount of depression and elevation would depend upon the angular velocity of rotation.

3. In the deformation of the sphere no fluid would have flowed in a current from the region of depression to form the protuberance. It would be a mistake to say that no fluid can rise in a protuberance "unless it has come from the region of depression," or "through great distances."

4. If the sphere were composed of a perfect fluid, the depression and elevation would take place simultaneously. No time would be required beyond that in which difference of pressure existed; that is to say, no time would be required beyond that occupied by the fluid in rising through the height of the protuberance.

Current motion requires time in which to convey fluid horizontally from place to place, but pressure is transmitted in a perfect fluid instantaneously, and depression of any part of a sphere could only take place simultaneously with the elevation in other regions. This may be illustrated by filling a hollow elastic sphere with water, when compression, as between finger and thumb, will be found to depress one part as another rises without creating any current. Time is not an element in the calculation of the effect of pressure in a perfect fluid. Water is almost a perfect fluid, and what is true of a sphere composed of a perfect fluid is practically true of one composed of water. Pressure is transmitted in water practically instantaneously.

5. The deformation of the sphere by rotation into a spheroid would be permanent as long as the rotation continued equable. As there would be no alternate rise and fall there would be nothing tidal in the deformation, and so rotation has no tide-generating effect.

6. A rigid sphere covered with a coating of perfect fluid would have the fluid elevated in the equatorial regions by rotation and depressed towards the poles (provided that the coating were of sufficient depth to allow the depression to take place without denuding the poles of fluid) until the pressure towards the centre became equal on all sides, the amount of depression and elevation depending upon the velocity of rotation.

No motion in the shape of current would be produced whilst such deformation was taking place, the depression and elevation occurring simultaneously. Again, the results if the coating were of water would be practically the same as in the case of a perfect fluid, which I will henceforth assume water to be.

7. If, whilst the spheroid is rotating equably about a fixed axis, we introduce another body at right angles to the axis, mutual gravity will come into play and every particle in each body will attract every particle

in the other body. The attraction of the new body may be considered concentrated in its centre, and being greater on the nearer parts of the rotating spheroid than on the more remote parts will again disturb its equilibrium. The disturbance would, as before, be compensated by a rise of water on the side of the spheroid nearer the attracting body and a depression on the side which was remote.* The protuberance and depression would remain always in the same positions, the rotation of the deformed spheroid bringing the particles along each meridian line, in turn, through the protuberance and depression once in each rotation. There would in that case be one tide experienced on the rotating body in each rotation, high water on any meridian occurring when it passed between the centres of the two bodies and low water when opposite that position on the other side of the rotating body. It is manifest that rotation would have had no influence in generating the tidal protuberance and depression. Its only effect is that of bringing each meridian in turn through the shape which the attraction of the new body has caused the spheroid to assume.

8. In the passage of each meridian in turn through the region of elevation and depression, no current motion would be created in the water. The particles along each meridian are throughout the rotation being continually and momentarily placed in the same positions (with respect to the attraction of the new body) that were occupied the previous moment by the particles of the line immediately in advance of them (in the rotation), and that will next moment be occupied by those of the line immediately behind. The particles of water are thus being each moment exposed to attraction differing infinitesimally from that which affected them the moment before and from that which will affect them the moment following. They are each moment occupying positions in which the pressure on them towards the centre of the spheroid (slightly deformed though it be) is infinitesimally different from that of the precedent and succeeding moments, but difference of pressure does not create current in a perfect fluid, or water, and the only motion will be that of ascent and descent as the particles momentarily replace others which were higher or lower than they were.

9. To make the matter clearer, since rotation has of itself no tide-generating force, let us suppose the fixed sphere to be deprived of rotation and the other body introduced as before. Then the attraction upon the sphere will tend to counteract its gravity on the side next the attracting body and will counteract it most at the point of its surface between the centres of the two bodies ; and it will have its gravity, or the pull upon its particles, towards its own centre increased on the side remote from the attracting body and most increased at the point opposite to that at which gravity is most counteracted. The difference of pressure will cause the fluid (or water) to rise where the pressure is least and to fall where it is greatest. Pressure is least on the side nearer the attracting body and the fluid will rise there. Pressure is greatest on the remote side and the water will fall there.

Tide is thus as far as we have seen the result of differential pressure caused by the varying effect of the disturbing body's attraction, and neither creates, nor is created by current.

10. We will now take another step which will bring us nearer to the

* It is assumed that there is a force so far counteracting their mutual attraction that the two bodies cannot approach one another.

phenomena of Nature. We have hitherto sought, and I think found, the explanation of tide, but only of one tide in each rotation of a body or planet. But we know that on our own planet there are two tides, not indeed exactly in each rotation of the earth, but in a little more than a rotation. The existence of the second tide is as far as we have gone still a mystery. It is, however, capable of a very simple explanation. Neither the earth nor the moon are fixed in space, but are *both* revolving about their common centre of gravity. This common centre of gravity (which we will henceforth designate as the point G) is on the line joining the centres of the earth and moon, and owing to the great weight of the earth as compared with that of the moon about 1000 miles beneath the surface, and consequently only about 3000 miles from the centre of our globe. The moon therefore revolves about G in an orbit of some 236,000 miles radius, while the earth's centre revolves about G in the same period (a lunar month) in an orbit of some 3000 miles radius.

Now, the earth and the moon are being always drawn together by their mutual attraction, but they do not approach one another. Why? Because the velocity of each in its orbit is sufficient, and but just sufficient to develop precisely the amount of centrifugal force which counteracts the attraction, and keeps them at the same distance from one another. Centrifugal force and attraction or centripetal force then exactly balance one another, *i.e.*, they are exactly equal.

Whilst the practical immutability of the moon's distance throughout countless centuries conclusively proves their equality, the different nature of these forces makes it perfectly clear that the equality only holds good for some particle near the earth's centre and all other particles having this same distance from the moon. The centrifugal force of revolution is the same for every particle in the earth, and if the attraction of the moon was also the same at each point, the two forces would be accurately balanced everywhere and there would be no tides. But attraction or centripetal force varies inversely as the square of the moon's distance, and is consequently greater on the side next the moon and less on the side remote from the moon than at the earth's centre, and greatest and least at the nearest and furthest points on the surface. Thus, whilst the two forces are equally balanced on the whole and on the average, there is an excess or overbalance of attraction on the side next the moon and an overbalance of centrifugal force on the remote side. These "overbalances" are the tide-generating forces. The first raises a cone of water under the moon to form the lunar tide; the latter another cone diametrically on the opposite side of the earth to form the anti-lunar tide. Thus the effect of orbital revolution is to reduce the volume of what would be a very large single tide (already considered in 7 and 8) by forming a similar tide on the opposite side of the earth. The tidal protuberances are conical because the overbalances increase from zero at the earth's centre to a maximum at the points under and opposite to the moon.

Rotation, as in the case of the single tide, has nothing to do with forming the overbalances, as the force generated by it is centrifugal only from the earth's axis, and is directed equally towards and from the moon, and consequently can neither increase nor diminish either of the forces of orbital revolution.

Whilst rotation has thus no power to modify in the slightest degree the amount of rise and fall of the surface of the ocean, it plays a most

important part in regulating the intervals between high and low waters, or the frequency with which tides recur, as this depends upon the ratio between the periods of revolution and rotation, and the more nearly they coincide the fewer tides will be produced.

If the moon revolved in the same period as the earth requires for a complete turn on its axis, the tidal cones would exist, but (neglecting the effect of declination and supposing the moon to be always over the equator) their positions would be fixtures and as little noticeable as our equatorial bulge. The moon would remain over the same spot on the earth, and there would be permanent high water under and opposite to her and continuous low water half way between these places. There would be no rise and fall. If we double this period of revolution by assuming it to be 48 hours, rotation will cause every meridian to pass through the cones once in this interval and two tides would result (one lunar and one anti-lunar). If we increase the period to 20 days the earth will rotate under the moon 19 times and we would have 38 tides. The moon actually revolves in about $29\frac{1}{2}$ days,* and the earth then rotating under her $28\frac{1}{2}$ times, we have 57 tides in a lunation.

This statement of the case, based on the laws of motion, gravity and hydrostatics, and upon self-evident truths, is, I believe, incontrovertible, and proves the first three of my contentions for the ideal world; but if we want any further confirmation of tide being due to pressure and not to current, we have only to apply to the barometer. It is admitted that a rise of 1 inch of mercury produces a depression of 20 inches in the surface of the sea, so that a rise of a little over 2 inches would neutralise the elevation of the tidal cone and keep the surface at mean level.

The theory which I have been leading up to and have now briefly described, in which current motion is as unnecessary as I believe it to be impossible and inconceivable, is the equilibrium theory, as we interpret it for the ideal world.

The world upon which we live differs from the ideal world, in that the ocean is not uniformly deep (in places it is comparatively quite shallow), and that a large fraction of its surface is dry land, especially in the northern hemisphere, whilst even in the southern half the continent of America stretches right across their path beyond the limits of the tidal cones when the moon is over the equator. Australasia is within 500 miles of the circle of mean level,† and the south point of Africa between the two is only 1100 miles from it. Besides these visible obstructions to the passage of the tidal wave it is a well-established fact that shallow water retards more or less according to depth and the steepness of the shelving bottom, the progress of all waves however produced.

Notwithstanding these obstacles and checks, I think we are justified in assuming that the tides on our globe will obey the laws established for those of the ideal world as nearly as the impediments to the passage of the wave form will permit. The only portion of the surface of the earth fairly free from interruption and retardation, and so approximating to the conditions of the ideal world, is the great Southern Ocean, where, at the

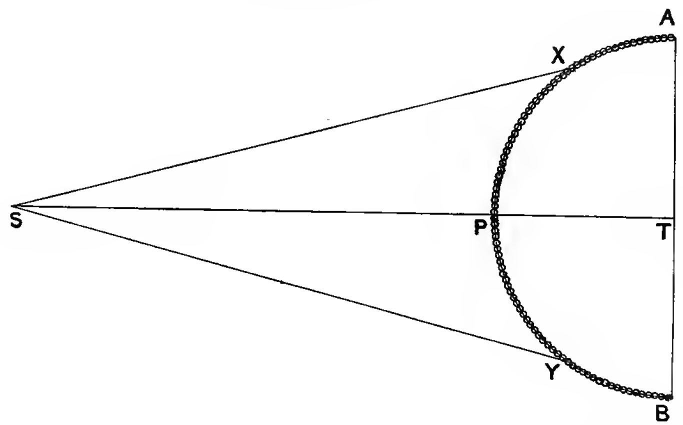
* The moon makes the circuit of the heavens in 27·32 days, and as in this interval the earth has advanced some 26·9° in her orbit, the moon requires another 2·21 days to overtake it and complete the lunar month, or synodical period, of $29\frac{1}{2}$ days.

† The circle of mean level is the same as a navigational circle of equal altitude = 35° 16′ when the zenith distance would be 54° 44′ = 3284 nautical miles.

few stations that tides have been observed, they confirm the theory we have advanced. Thus, at the southern extremity of New Zealand the tide is under the moon, although such is not the case at any other point on the coast, owing to retardation caused by the shallowing sea-floor and obstructing land. At Kerguelen Island it again arrives with the moon. On the co-tidal chart compiled by Sir George Airy and published in the *Encyclopædia Metropolitana*, the tide is under the moon in this same ocean as far north as the 45th parallel of south latitude, and it, or a very similar chart, is reproduced in the *Encyclopædia Britannica*. A further very practical proof of our theory is that, assuming the principles I have enunciated as correct, we have been able to explain large numbers of tides hitherto called anomalous and admittedly incapable of interpretation by the orthodox theory. No tidal currents have ever been observed in the open ocean, and all those nearer the shore are caused by opposition to the free action of the tidal waves. When obstructing land raises the surface of the sea above that of adjacent water, a current is naturally set up to restore the level.

The tide-generating force can be resolved into rectangular components, one normal or perpendicular to the earth's surface, and the other acting tangentially. Under the moon there is no tangential component, the whole force acting with its greatest intensity normally and *outwards*. From this position the normal component decreases till it becomes zero at a point where the whole force acts tangentially with seven-tenths the intensity it had under the moon. Beyond this point the normal component reappears, but acting *inwards* till in quadrature, where the tangential component again vanishes, it assists the earth's gravity with exactly half the intensity that it had under the moon. Thus the normal component in conjunction is elevating the surface and in quadrature creating a depression. From the point of its greatest intensity, the middle of the quadrant, the tangential component decreases gradually both towards conjunction and quadrature, at which points, as already stated, it is zero. Whilst the effect of the tangential component is not at first sight so obvious, it is the most effective tide-raiser of the two, as I will now show :—

Diagram VIII.



If in the diagram the circle represents a section of the earth with T as its centre and S the moon (which is in reality 60 times P T distant),

the semi-circle A P B may be taken to represent one line out of the infinite number of lines of surface particles from every point of the compass that would be under the horizontal pull of the tangential component towards the central point P of the superficial coating of water. Then the tangential component of tidal force is drawing every particle (as X) along the part of the circle between A and P towards the latter point; it is also drawing every particle (as Y) between B and P towards the same point and the whole coating of water is composed of an infinite number of such lines of particles lying one upon another from the surface to the bottom of the ocean. Every particle in A P and every particle in the infinite number of lines under A P is being drawn with exactly the same force towards P as the similarly placed particle in B P, or one of the lines under it is being drawn towards P. What is true for these two lines of particles holds good for lines in each layer from every point of the horizon.

As then at P every line of particles is met by a similar line of particles, a perfect block is established at P, and no line of particles can make any progress in the direction in which it is being drawn. The pull on every particle in each layer being exactly balanced by a similar pull on the corresponding particle on the opposite side of P, no current can result, but only an accumulation of pressure, which is accentuated by the convergence of the lines. There is at P the integration of all the pressures on particles in every line and every layer towards P. Under this integrated pressure the water will rise till the weight of elevated water balances the pressure. This integration of pressure through what is called a "fictitious horizontal depth" is very much greater than the accumulated normal attraction through the mere depth of water, but both components of the tide-generating force work together to produce hydrostatic equilibrium, principally, if not wholly, by vertical movement of the particles of water and without creating any current.

11. I believe that the theory we have evolved is very similar to Newton's original conception. At whatever stage, however, he concluded that current was the only means of producing equilibrium, he must have got the idea from watching the tides round our coasts, and when, in his endeavour to fit his theory to them, he penned the 18th and 19th corollaries of Prop. 66, Book I., of the *Principia*, he inadvertently exchanged revolution for rotation, and their effects, as I have shown, are totally different. Laplace introduced both these oversights into his dynamical theory, which has covered the face of the globe with anomalies that no expert has ever been able to explain or reconcile with the principles he laid down. By the dynamical theory the tidal wave, being unable to keep pace with the moon as a free wave, dropped back to quadrature, in which position the tangential component drags it round with the velocity it was incapable of under the moon. But as I have already stated, there is *no tangential component* in quadrature, and the normal component is *depressing* the surface. The motion of the tidal wave is compared to that of a pendulum which oscillates to and fro, whereas the wave travels continually in the same direction. The principle of forced vibrations is used to explain the so-called inversion of the wave which would only be semi-inverted in quadrature. We contend that there is no analogy between the motion of the tide wave and that of a pendulum, and that the only oscillations of the tide are the vertical rise and fall of the water and the swing of the cones across the equator.

Sir George Airy, in describing the dynamical theory, says that a small vertical rise entails an enormous horizontal movement (something like 1000 times the rise), but this is easily disproved by experiment. Take a long horizontal tube of uniform bore with vertical ends. Nearly fill it with water, so that the fluid stands several feet high in the upright portions. If now we depress the surface in one end of the tube by means of a tight-fitting piston, there will be a corresponding rise in the opposite end. It is obvious that every particle of water will have moved through the same distance, whether it be in the upright or horizontal portion of the tube. We may increase the length of the tube as we please to one-quarter, or even half-way round the world, and the result will be the same. So far from the horizontal movement being a large multiple of the vertical rise, it will not exceed it by the minutest fraction.

The dynamical theory necessitates currents from every point of the horizon. Those from east and west must change about every six hours, and the meridional ones would be deflected by rotation, creating vortices. Now it is quite true that there are currents in the ocean, but with one or two trifling exceptions they are variable in strength, direction and duration, and are the most uncertain element the navigator has to deal with. The tidal currents and vortices of the dynamical theory have never yet been experienced by any of the hundreds of thousands of deep sea navigators traversing the seas since the days of Columbus and Magellan. If they existed, they would render the ocean unnavigable, or at least make navigation a much more uncertain art than it is.

Laplace concluded that in an ocean of equable depth, there would be no diurnal inequality, which would in any case, according to his theory. decrease to evanescence as we attain high latitudes. Now diurnal inequality is simply the difference between two semi-diurnal tides, or the heights of two successive high waters, and whilst the anomalous tides of Northern Europe seemed to support the great French astronomer's view and perhaps suggested it to him, the numerous tides observed since in all parts of the world emphatically contradict it. In the Pacific Ocean the depth is more uniform than elsewhere on the earth, and yet diurnal inequality is almost universal. On the coasts of Siberia and British Columbia, where by dynamical principles it ought to be disappearing, it is so great that there is but one high and one low water in the lunar day. But if the cones were where the dynamical theory places them there could be *no diurnal difference*, and the tidal experts have always to use an equilibrium diagram to explain it, as I will now demonstrate.

If the reader will turn to Diagram I., p. 11, he will see that when the moon is over the equator she will be in the direction Q E produced. Then by the equilibrium theory the cones will be at E and Q, whilst the dynamical theory places them over and under O. In neither case would there be any diurnal inequality. But suppose the moon to be in the direction H M with extreme northern declination. Dealing first with the equilibrium theory, the cones following the moon would be at H and H′. Then L W will represent the centre of a band (70° wide) of depressed water running round the earth midway between the cones. As the earth rotates on P P′ a place situated on the parallel of latitude H V will when at H be in the apex of the tide and have the highest water possible. As it is carried by rotation eastwards it will, at B after a long ebb, be in absolutely lowest water. Then a short flood will produce another high water at

V, but not nearly so high as at H. The cone extends for 55° each side of H and H′ and V is 58° from H′ and so actually beyond the circle of mean level indicated by the dotted line. From below mean level at V it will be carried by rotation again to lowest water as it crosses the continuation of L W (behind the diagram), and at the expiration of a lunar day back to highest water at H. If our place was on the ideal world and marked by a graduated tide pole, it is clear that a large diurnal inequality would be indicated. As far as obstructions permit the same result would be produced on our globe. Now let us take a place on the parallel R W. When it is at R it will have highest water possible on that parallel. R is 32° from H, or more than half-way towards the circle of mean level. In half a lunar day the place will be carried to W, where it will be in absolutely lowest water and in another 12 hours 25 minutes it will be back at R in high water. There will have been only one high and one low water in the lunar day. Thus whilst at the equator there would be no diurnal inequality (because Q is the same distance from H′ as E from H), in latitude 29° under the moon it will be very considerable and on the parallel which is the same distance from the pole as the moon from the equator, it will be so potent as to reduce the two tides to one. It must be evident too, that there will be a considerable range of latitude adjacent to the single-day parallel over which there will practically be only one high and one low water in the lunar day.

The same reasoning holds good for the corresponding parallels on the other side of the equator, except that, as I have shown elsewhere, diurnal inequality is never so great on the side of the anti-lunar tide.

Now, these theoretical tides correspond in every particular with the single-day tides of the Pacific, except that the latter are not under the moon, but that is entirely due to the retardation we might expect from their surroundings. The tidal spheroid is there distorted by land, and each tide is that which if its progress had been unobstructed would have arrived earlier and with the moon. I predict with confidence that similar tides will be found *under the moon* at all the islands in high southern latitudes which have an unobstructed approach for the tidal wave, such as the South Orkneys in 61° S., the South Shetlands in 62° S., Bouvet Island and Macquarie Island in 55° S.

Now let us turn again to the dynamical theory and apply the inequality test to it. A reference to the figure will make it clear that with the cones in quadrature they will be over and under O, no matter what the moon's declination may be, and so even when she is in the direction H M the large outer circle P Q P′ E will represent that of lowest water. A place on the parallel H V will when carried round by rotation cross the circle over P O P′ and its continuation on the far side of the diagram at the same distance from the cones (now permanently located on the equator), and the two high waters will have equal elevation. It is also evident that there will be no difference between the low waters at H and V. On the parallel R W we get a similar result, except that the tides are smaller because they are farther from the apices of the cones. A place situated on that parallel will have two similar low waters when it crosses the circle of greatest depression at R and W, and two relatively high waters which, while not attaining to mean level, will be exactly equal in height.

Briefly, the cones and depressions would travel slowly round the equator. As a place in any latitude overtakes them by rotation it must

pass each cone and depression at the same distance, and so there could be no inequality in either rise or fall, except the infinitesimal amount due to change of declination. Thus there could be no diurnal inequality and no single day tides, but we know that Nature produces both, and that the latter were described by Airy as "most remarkable," doubtless because by the theory he was advocating he could not account for them. Any of the objections that I have urged would be a severe blow to the dynamical theory. Collectively they lead irresistibly to the conclusion that it is radically unsound, and so I claim to have proved the fourth of my contentions that the dynamical theory is untenable.

The same principles apply to the production of solar tides, which, however, are smaller owing to the much greater distance of the sun. Whilst his total attraction largely exceeds that of the moon, it is evident that the *difference* between his attraction on a particle on the near side and one on the remote side of the earth will be less than in the case of the moon, where this difference is that due to one-thirtieth of the whole distance, and so the tide-generating force is less. Two solar tidal cones are, however, formed by the attraction or centripetal force of the sun and the centrifugal force of the earth in its revolution round the sun, or rather round their common centre of gravity. These solar tides would be well marked if they stood alone, but as it is, they are principally observable as increasing and reducing the larger tides raised by the moon.

The earth goes round the sun in a year, and the differential attraction of the sun and centrifugal force of the earth in her annual orbit cause two solar tides in a year at any place on the earth. The moon goes round the earth in a lunar month, and the attraction of the moon and centrifugal force of the earth in her lunar monthly orbit give two tides at each place in a lunar month. These are the only tides that are raised, or to raise which there is any tidal force. Of these twenty-six or twenty-seven in a year, the only tides that we are conscious of are the twenty-four or twenty-five raised by the moon. The solar tides move round the earth with a velocity of about three miles per hour, which is not a great speed for a wave-like movement; the moon's tides have a velocity of some 34 miles per hour, in both cases along the equator. The rotation of the earth on its axis carrying the surface water through these protuberances gives us our 728 solar tides, which are not noticed as separate tides, and our 705 lunar tides, which are noticed and recorded in our tide tables. If the lunar and solar tidal cones were fixtures rotation would give 730 of each in a year, but just as the navigator loses a day when sailing round the world westward so the sun annually loses a pair of tides, and the moon going round the earth $12\frac{1}{2}$ times in a year loses 25 tides, and there are $730-25$ or 705 lunar tides in twelve months. The lunar cones travelling so much faster than those formed by the sun and all moving in the same direction as the earth is turning on its axis, any given place requires more time to be carried by rotation from one lunar cone to the other, than from one solar cone to the other. Those produced by the sun travelling rather more than 30 miles along the equator to the lunar 29, slowly but continuously overtake and pass the larger cones. When they are together and superimposed we have spring tides; when they are half way between we have neap tides.

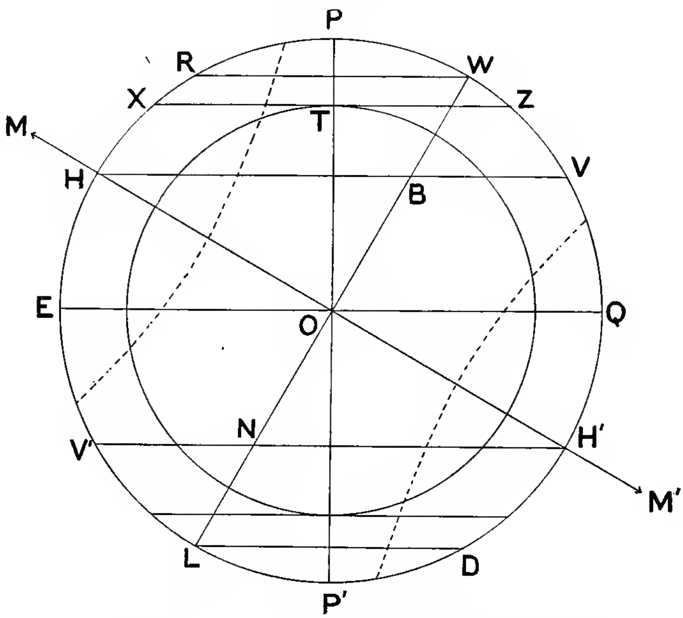
Axial rotation has not the slightest influence on the tide-generating forces. It makes no difference to the attractions of the sun and moon

that the earth rotates ; it makes no difference to the centrifugal force of the earth in her orbit that the earth rotates. It is upon these two forces alone that tide depends. These forces alone raise the tides, and would continue to do so even if rotation were to cease. Rotation only carries the earth "with its coating of water" through the tidal protuberances. It has not had the very least part in producing them, and yet rotation is treated by every orthodox tidal theorist from Laplace onward as if it like revolution was a tide generator.

CHAPTER VI.

On p. 208 of the Admiralty Tide Tables (1902) we find the following note on the tides of Burrard Inlet :—" From September to March the day tides are highest, the reverse occurs during the other months. The diurnal inequality is great, causing apparently but one tide in the 24 hours on many days. The tide has the peculiarity of rising to nearly the same level at the higher high water whether it be springs or neaps, whereas the level of low water varies in the usual manner." And on the same page :—" The tide, so far as ascertained at places in the Strait of Georgia and to the northward as far as Seymour Narrows, has the peculiarity of rising to nearly the same level at the higher high waters whether it be springs or neaps, whereas the level of low water varies in the usual manner." These places are between Vancouver Island and the mainland of British North America in latitude 49°– 52° N. and longitude 124°–129° W., and are within 10° or 12° of the parallel of single-day tides when the moon has high declination, and so our theory would predict very great diurnal inequality. I will now endeavour to make it clear that what is a "peculiarity" by the dynamical theory is explicable by, and a necessity of, the new equilibrium theory. Let us

Diagram IX.



compare the proportionate values of spring and neap tides along the parallel $\text{Cos.}^{-1}\frac{1}{\sqrt{3}}$ = Lat. 54° 44′ N., at summer solstice and autumnal equinox. If in diagram the inner circle be drawn with radius O T = nat. sin. to radius O P, it will just touch the parallel X Z, which will

represent that of 54° 44′, a very few degrees north of the localities mentioned in the explanatory notes. This inner circle (lunar circle of equal altitude 35° 16′) will represent that of mean level* at *equinoctial springs*, or when the moon and sun are both over O. The outer circle will then represent that of lowest water. Let H M be the direction of the moon at *summer solstice* (21st June) and at new moon it will also nearly enough for our purpose be the direction of the sun. Then the dotted lines will be the circles of mean level[1], and L W that of lowest water. R W will be the parallel along which it is impossible there can be more than one true tide in the lunar day. X and Z are both 54° 44′ from the equator, and so at solstitial springs X is 26° from the apex of the cone of the day tide at H, whilst Z is 83° from H′ and therefore in almost lowest possible water. It is clear that at this new moon the day tide at X will be large, whilst the night tide at Z practically vanishes. At most the elevation at Z can be little above lowest water, and there will be thus at solstitial new moon a great diurnal difference in the elevation of the day and the night tides, amounting practically to only one tide in the lunar day.

Let us now see what the neaps will be. A week after new moon that luminary will be over O on the equator, and her high water will vanish at T, which will have as far as the moon is concerned water at mean level. X and Z will both be in her lowest water. As a place on this parallel is carried by rotation through these points, it is plain that the high waters at T and opposite T (along the parallel) will be but relative, that is as compared with the depressions at X and Z, which are both on the circle representing the moon's lowest water. But the depression at X will not be nearly so low as that at Z, because the sun will have scarcely moved perceptibly south during the week and will be still exerting his influence over H, and so producing solar high water at X, whilst Z is so far from H′ as to be almost in solar low water. The two high waters at and opposite T will be equal, but the depressions will be unequal. The high waters being but relative, will this neap tide be less than the spring day tide and greater than the spring night tide? What was practically a single-day tide at springs along the parallel of 54° 44′ has given place at neaps to two equal high waters of moderate elevation in the lunar day with two very unequal low waters.

Now let us see what the tides will be proportionately to one another (spring and neap) at the autumnal equinox. About 21st September the sun will be over the equator at O, and the moon, if new, will be in the same direction between the sun and the earth. The equinoctial spring tide will, therefore, be highest on the equator, and its elevation will vanish at T. From T to the pole there will be depression. Thus at equinoctial spring tide there can be no elevation above mean level along the parallel X Z. There will be two low waters at X and Z (lowest possible), and therefore a relative high water at T and opposite T, but the highest water will not be above mean level. So much for the equinoctial spring tide along the parallel 54° 44′.

What of the equinoctial neap tides? A week before equinoctial new moon, just considered, she was entering her last quarter and 6 hours west of the sun, which was practically over the equator, whilst the moon

* For the moon and approximately for the sun. The circle of lowest water is the same for both luminaries when sun, moon, and earth are in line.

was in the direction H M. The moon was, therefore, producing her highest water at H, and high water (though, of course, not so high) at X, which is 26° away from the apex of her tide. At Z the tide produced by the moon may be considered as practically at low water. The sun's tide almost vanishes along the circle through T, and the circle P Z Q P′ E gives his lowest water. The tide at X is therefore the moon's tide at a point 26° away from her, diminished by the depression produced by the sun's influence. Practically there will be but one high water along the parallel of 54° 44′ in the lunar day, but its elevation will be greater than that of either of the semi-diurnal equinoctial spring tides and higher than either of the equal high waters at solstitial neaps.

The parallel of 54° 44′ has been selected to simplify the demonstration and to better contrast the two extreme cases of no declination and highest declination for the tide-producing luminaries, but it is obvious that what is true for this parallel must approximate very closely to the theoretical tides of the localities mentioned in the Tide Tables, which are only from 2° to 5° south of 54° 44′. To those who are accustomed to see spring tides greater than neaps at all seasons of the year, it may seem an astonishing result to find practically a single high water in the day at solstitial springs, and the same at equinoctial neaps higher than the preceding and following springs, but it seems theoretically necessary unless counteracted by local conditions. If this be so, it is clear that the notes quoted describe the tides as they should occur, and there is no peculiarity to explain. If, on the other hand, our views are false, it must be considered a strange coincidence that our theoretically necessary tides should agree as far as obstructions permit with the facts of observation.

It is quite certain that the tides of Burrard Inlet and the Strait of Georgia cannot be accounted for on dynamical principles, and before Moxly's explanation twelve years ago mariners navigating these waters were at a loss to know what to expect, whether the neap would change places with the spring tide as regards height, or whether to look for two high waters or one in the lunar day. Ten years ago the Canadian Government commenced to publish Tide Tables for this coast, which have been annually improved as observations accumulate and are analysed, and now, under the able direction of Dr. Bell Dawson they seem to leave little to be desired as practical guides. The tides themselves are, however, no longer "anomalous," but are the true equilibrium tides interfered with as they must be by natural obstructions.

Let not the reader lose faith if some of these published and valuable records seem at first sight to contradict our theory, but rather, when he has the opportunity, endeavour by comparing theory with actuality, to find out the cause of discrepancies and how obstructions produce them. With a true theory, now that systematic observations are being taken and analysed, it is only a question of time for a careful comparison of times and heights at various stations along the coast and speed of streams through connecting channels, to unravel the skein and reveal Nature's secrets here, as we have done in so many other simpler cases, where till comparatively recently the tides were called "anomalous." That actual and relative heights as well as times may, owing to the effect of local surroundings, be expected to differ from those predicted by theory for a world free from obstructions, is indicated by such facts as

that on 26th March, 1910, when the moon and sun weie over the equator and quite incapable of producing any diurnal inequality whatever, the tables for Vancouver, B.C., showed 16 inches inequality in a rise of 11 feet. This, of course, like the extra 7 feet of rise, must be entirely due to local causes. The same thing occurs on the British coasts. Opening the Tide Tables for 1902 I find that at Devonport on 17th September, with the luminaries over the equator, the difference between high waters was 10 inches and between low waters 11 inches, which is clearly not due to declination. On 20th June the tide which should theoretically be considerably the lower had 6 inches more elevation. The reason for this will appear presently. Another apparent anomaly and contradiction to rule, is that the day tides at Burrard Inlet are highest in winter and night tides in summer, but that is only because they have to search their way over shallows for such a long distance from the coast. The same way the tides that at Halifax and St. Paul's Island, in the entrance to the Gulf of St. Lawrence conform to our rule, require nearly another 12 hours to reach Quebec, and considerably more than 12 hours to arrive at Montreal, and so the coast day-tide becomes a night tide, and the night tide belongs up the river to the following day.

It is worth while to tabulate the foregoing results for easy reference, because they apply not only to the places named, but to all others a few degrees either side of latitude 55° N. and S. as far as the permanent obstruction of land and uneven depths, and temporary interferences, such as abnormal atmospheric pressure and wind friction, will permit.

At Solstice.	Springs	Great diurnal inequality, so that there is practically only one high and one low water in the day—high water highest possible on that parallel: low water nearly lowest possible anywhere; of long duration with slight rise at half-time.
	Neaps	Two equal high waters (lower than spring day tide and higher than night tide) not much above mean level, with two very unequal low waters, one being largely counteracted by the sun's attraction and the other coincident with solar low water.
At Equinox.	Springs	Two equal high waters not much above mean level, with two equal depressions to lowest water possible. Range not great.
	Neaps	Great diurnal inequality, amounting to practically one tide in the day. As the sun is subtracting from the lunar tide, the elevation will be less than at solstitial springs, but higher than at solstitial neaps, or equinoctial springs. Low water nearly lowest possible.

The Admiralty Tide Tables tell us that at some places on the east coast of British North America, diurnal inequality affects low water more than high water. The reason now is quite clear. The sun modifies one low water and accentuates the other at solstitial neaps, and for some time before and after to a lesser degree. Between solstice and equinox intermediate conditions and results will obtain, inclining towards one or the other, according to the position of the tide-producing luminaries.

If the critic objects that our diagram does not explain the tides about the entrance to the British Channels, where there is little difference

between the elevation corresponding to the moon's passage of the upper and lower meridians, my reply is, that the tides of the North Atlantic are largely, and perhaps in some places principally, derived from those of the South Atlantic, and so only partially conform to the differential pressure theory. As far as the *true* tide is concerned it obeys the statical law, and is the same as if there was continuous land round eastward from the western shores of Europe to the eastern coast of America. The whole level of the North Atlantic will, however, at regular intervals, be raised by the derived tide travelling from the southward as a free wave for thousands of miles over uneven depths, and consequently at variable speeds, especially on the eastern side, where islands as well as sloping sea-floors obstruct its path. It is now generally agreed that this derived tide is the cause of the enormous rise in the Bay of Fundy, and I believe that a closer analysis will show that it counteracts or almost annihilates, and in some cases reverses, diurnal inequality in the tides which we maintain misled Newton and Laplace. If I put this forward more as a highly probable suggestion than as an assertion, it is only because I have not sufficient evidence at hand to prove it indisputably, but I think I can convince the reader that it is almost a certainty.

To begin with, the fact remains that in similar latitudes in other oceans, where any derived tide is so small as to be practically a negligible quantity, diurnal inequality is almost universal. Reasoning by analogy suggests that it would be equally regular in north-west Europe, if there were not a compensating wave or equalizing pressure from some direction that modifies it and in some places annuls it. This wave can hardly come from the east or the north, nor yet from the west, towards which the *true* tide wave must be travelling. There only remains the south and south-west, the direction that the derived tide wave comes from.

Again, as tidal observations became numerous, it should have been, and is now evident, that the few particulars available as practical guides to Newton and Laplace were not typical of Atlantic tides generally, nor even of those of western and north-western Europe in particular. More than 70 years ago Whewell found that diurnal inequality was quite general, if small, on the west coasts of Spain, Portugal, and France, except, of course, when the moon was on or near the equator. He found that it obtained on the coasts of Cornwall and Ireland for part of the lunation, after which it suddenly vanished. There was some diurnal inequality in the North Sea, whilst on the other side of the Atlantic it equalled in the Bay of Fundy some of the differences between springs and neaps. He found that maximum inequality corresponded to maximum declination, which the equilibrium theory postulates, and that inequality of heights depends partly upon local circumstances, which agrees with our contentions as to the effect of obstructions.

Whewell's examination showed that in the Southern Hemisphere when the moon was south of the equator, the highest equilibrium tide (he had to call it an equilibrium tide because the dynamical wave was incapable of producing inequality) was that corresponding to the moon's upper meridian passage, whilst when she was north of the equator the highest tide was when the moon was on, or near, the lower meridian, which is in accordance with theory for the ideal world. He observed however that in the Northern Hemisphere the rule was reversed, and that the highest equilibrium tide, when the moon had northern declina-

tion, corresponded to her inferior transit, and when she had southern declination to the superior transit. This is contrary to theory for the ideal world, and doubtless, as I hope to show the reader, due to the influence of the derived tidal wave from the Southern Ocean.

Whewell considered that he detected a connexion between the tides of Liverpool and those of the Southern Ocean, 6,600 nautical or 7,600 English, miles away, allowing for the time it would take a free wave to travel this distance. He stated that it was not possible to give the law of diurnal inequality, that at one season of the year made day tides greater, and at another less, than night tides. This is a necessity of our theory, and as I have already shown, quite simply explained by it.

In a practical work on the tides, from which I have derived much valuable information, and which generally supports our views, I have seen it stated that the derived wave from the Cape will oscillate, inasmuch as it must reverse its direction of translation when the depressions pass the Cape of Good Hope. At first sight the idea appeared plausible, but a closer examination showed me that it was erroneous, and that even here there is no "oscillation." As the tidal cone approaches the African Continent, it must increase its elevation by reason of the obstruction, and this will set up derived waves (or currents) in the lines of least resistance to restore the level. Whilst some of the water doubtless finds its way to the northward, it seems probable that the bulk of it, assisted by the trend of the African Coast, will be deflected to the southward, where there is more open sea, and help to raise the comparatively higher level off the Cape, which generates the derived wave towards the equatorial region of the Atlantic. The surface of the ocean is already higher there than in the Atlantic, where the land has acted as an effective block to the passage of the tidal wave, and this relative increase in elevation over that of the water farther north generates a free wave to restore the level.

The problem is complicated by the fact that it is not a single wave that is generated, but rather a series of waves, commencing when the surface west of the Cape first rises above that of the ocean to the northward, and continuing until the level ceases to rise. Each wave may be conceived to give a fresh impulse to those in front of it and so diminish the retardation due to surface friction. When the depression passes the Cape there will be no obstruction to the moon's action in drawing the water away from the west coast of Africa, and consequently there will be no derived wave generated, or check to the one already travelling to the north-west. Thus the elevation generates a derived free wave, and the depression has no effect in checking it, and any retardation in its speed will be caused by atmospheric friction and that due to diminishing depths. On the east coast the effect will be different. Just as the land here increased the elevation by obstructing the passage of the wave, it will limit the depression by intervening between the moon and the water of the Indian Ocean. As the water cannot follow the moon across the African Continent, it must be kept at a higher level than that south of the Cape of Good Hope, where she has full power (for that latitude) to create a depression, and again a derived wave or southerly current must result.

To what extent Atlantic tides are affected by this derived wave, observation rather than theory will eventually decide, but as observations become multiplied at stations, especially the islands along its path, data

ought to be forthcoming for an exhaustive analysis, which by separating if from the true tide would indicate their respective parts in producing the times of high water and elevations as we know them. That the derived wave is delayed by friction and obstructions is certain, and that the retardation is considerable seems evident for the following reasons. The highest *true* tide in the North Atlantic must as elsewhere in that hemisphere with northern declination be that nearest the moon, when the highest tide in southern latitudes is twelve hours to the eastward. Now this anti-lunar high tide would arrive off the Cape some twelve hours later, when the moon both there and at Greenwich is near the lower meridian. If the free wave it generates took only 12 hours to reach the neighbourhood of Ushant, it would meet the moon at her next return to the upper meridian and thus increase instead of reduce the amount of diurnal inequality. But Whewell tells us that the highest tide, when there is any difference, corresponds to her inferior transit, so that the derived wave must take nearer 24 than 12 hours to cover the distance and bring such a volume of water to swell the smaller true tide, that its level is raised to equal, or even exceed that of the larger one, and so diurnal inequality is annulled or perhaps even reversed. The average depth along the eastern side of the South Atlantic is about three miles, and in the North Atlantic does not exceed two miles, the appropriate wave speeds for which are 500 and 400 miles an hour if unobstructed. But besides the retardation caused by friction, every portion of the wave towards the Bay of Biscay and for 400 or 500 miles west of Cape Clear passes through a screen of islands. If we could move the Cape Verde Islands N. 5° E. 1100 or 1200 miles they, with the Azores on one side and Canaries, Madeira, &c., on the other, would form a barrier like a partially demolished gigantic breakwater across the path of the wave, which would be more or less broken up and checked passing through the comparatively shallow gaps between the islands. The check will hardly be much less because different sections of the wave receive it at different stages of their career. It is true that a portion of the wave passing west of the Azores in deeper water will outstrip that through the islands, and assisted by rotation and a rise of level be deflected towards north-west Europe, but the general effect on the whole wave will be a considerable reduction from its South Atlantic velocity of about 450 miles an hour. The position of the co-tidal lines west of Ushant and Cape Clear indicates that the tide is largely a derived wave coming to meet the moon and not following her as a true tide produced by an overbalance must do. If it arrives at the same time as a true tide, the highest water that their joint action is capable of will result. If earlier or later, the highest water will be less and at an intermediate time, inclining towards that corresponding to whichever of the two has the greatest elevating power.

The same wave will, an hour or two later, as it raises the level on those parallels, detach offshoots through the North Channel into the Irish Sea and round Scotland and the islands into the North Sea. The latter travelling at a much reduced speed in the shallow water proceeds south to meet another tide coming up the Channel, and is doubtless the cause of the highest tide in the Thames, following at such a long interval full and change of the moon. The faster moving section west of the Azores will probably feed the tides about the north of Scotland rather than those near Ushant and the English Channel.

The section of the derived wave towards the American coast has a clear run of about 7800 miles to the 100 fathom line in the deepest water of the Atlantic, where an initial speed of 500 miles an hour would be possible. There are no obstructions in its path, but its velocity would be gradually reduced both by bottom and atmospheric friction. If the wave left the Cape, with the moon on the lower meridian, it would have $17\frac{1}{2}$ hours to reach the coast of Maine under the luminary, entailing an average speed of 445 miles an hour, whilst an hourly speed of 370 miles would bring it there $3\frac{1}{2}$ hours behind her, which is a very moderate amount of retardation to allow for the lunar true tide.

With a view to testing how far Whewell's conclusions applied to the western side of the Atlantic and agreed with modern observations, I extracted from the admirable Tide Tables published by the Canadian Government five spring tides, near the summer and winter solstices, for the port of Halifax, on the coast of Nova-Scotia facing the Atlantic, and for St. John, New Brunswick, on the western shore of the Bay of Fundy.

Taking first the port of Halifax, I found that in each case the highest water followed the transit of the moon that agreed with theory for the ideal world, and at fairly regular intervals the mean of which was 7.7 hours, and is not an excessive retardation. This indicates to my mind conclusively that the dominant factor in producing the tides of Halifax is the forced wave of the true tide following the moon across the Atlantic, though doubtless the derived wave contributes its quota and probably modifies the times as well as the amounts of elevation and depression. Diurnal inequality was irregular, and from $\frac{1}{2}$ to $\frac{3}{4}$ the greatest difference between springs and neaps, which it was about equal to on the average. It was greater at L.W. springs than at either H.Ws. or L.W. neaps, indicating an interference that was no doubt due to the derived tide.

Turning now to St. John, each of these solstitial springs followed the transit of the moon required by theory, but at such a long interval as to be generally only half an hour before the transit whose synchronism would reverse the rule. Eleven and a half hours is too much retardation to expect near the coast, and there must be a supplementary cause. Here again it is doubtless the derived wave banked up against and deflected by the coast of Maine, which in this case dominates the situation, quadrupling the rise of Halifax, apparently reversing the law of diurnal inequality, and probably modifying the times of H.W. from those that would obtain if the true tide was alone responsible for them. The arrival of one wave is not necessarily coincident with that of the other, but any interval will probably be small. Once they join forces, they will pursue their course as a single wave. Diurnal inequality is not really reversed, as it is obviously the same tide that was following the moon on the meridian of Halifax, still further retarded by the slope of the sea-floor, and perhaps by blending with a slower moving, or later arriving, derived wave.

Whilst diurnal inequality is more regular than at Halifax, it is only about half the greatest difference between springs and neaps, which in some cases it equals. It indicates the interference of the derived wave, inasmuch as it is greater at springs than at neaps and at H.W. than at L.W., whereas I have shown that at solstice it should be greatest theoretically at L.W. neaps on the parallel of 55°; and the same rule holds

good only to a lesser degree for the parallel of 45°, which is between these two ports. Diurnal inequality vanishes, as theory indicates it should, at equinox.

The scope of Whewell's examination of Atlantic tides covers a much more extensive field than mine, and his work is doubtless accurate, but he was handicapped by trying to adjust his inferences to dynamical principles, and so failed to deduce what seem to me obvious conclusions from the evidence. He found "that the tides of Liverpool agree with an equilibrium tide produced in the Southern Ocean $37\frac{1}{2}$ hours before the moon's transit at that port and transmitted thither unchanged" . . . . "that the equilibrium theory expresses with very remarkable exactness most of the circumstances on the results obtained" . . . "that the tide in any place occurs in the same way as if the ocean imitated the form of equilibrium corresponding to a certain antecedent time" . . . and "that the changes in lunar parallax and declination are very well represented by the equilibrium theory."

When, in addition, we remember that he had to go to the equilibrium theory to account for the very existence of diurnal inequality, it must have been a blind faith in the infallibility of Laplace that made him still cling to the dynamical theory instead of reverting to its statical rival.

The almost complete absence of diurnal inequality about the coasts of the English Channel was one of the factors which misled Newton and Laplace. Had they known that in other parts of the world diurnal inequality was general and that at the south point of New Zealand and along the Southern Indian Ocean the tidal crest was under the moon, the dynamical theory would never have been heard of. This practical universality of diurnal inequality and its increase as the moon recedes from the equator is of itself a proof of the statical and refutation of the dynamical theory. It is a necessity of the one and impossible of production by the other (on the ideal world, or on our own globe, except where the tidal wave is interfered with by obstructions).

Whewell found that diurnal inequality was large and universal on the western shores of the Atlantic, whilst on the eastern side it was either non-existent, or small and occasionally reversed. He was the first to suggest that the great rise in the Bay of Fundy was due to a derived wave from the Southern Ocean, but as this explanation was ignored and presumably rejected by his successors, Moxly was unaware of it when he arrived independently at the same conclusion. Whilst Whewell was the first to see that the tides of the British Islands were connected in some mysterious way with those of the Southern Ocean, he could find no reason for the apparent want of connexion between the tides on opposite shores of the North Atlantic which the Admiralty Tide Tables tell us have never been explained to this day.* To the reader who has followed my argument, I am now in a position to supply a key to this long outstanding puzzle.

The tides are different because produced by different combinations. Briefly, there are when the moon is away from the equator two unequal tides in the lunar day, the largest being with the moon in the hemisphere she is over, and opposite her in the other hemisphere, the smaller in each case 180° distant along the same parallel. On the western side

* *Tide Tables for British and Irish Ports*, 1911, p. xxix., par. 4.

of the Atlantic, the higher tide of the southern hemisphere combines with the lunar (or higher) tide of the northern hemisphere, and 12 hours later the two smaller tides will come together. Consequently there is a great difference in the heights. On the European side the slower moving wave from the south meets the tide following that which its faster companion conspired with, and so the large tide from the Cape combines with the smaller northern tide, and the small southern wave with the greater northern tide; and thus equality in heights is produced.

To go more into detail, when the moon with high northern declination is 11 hours west of Greenwich, the anti-lunar tide has just passed the meridian of the Cape. I have shown that a moderate speed for the depth of water would bring it to the coast of Maine with the moon, or rather with the tide following close behind her. Until it gets near enough to the coast to be affected by retardation, the forced wave along the parallel of 45° will be travelling at the rate of over 700 miles an hour, whereas the free wave, averaging about 400 miles an hour, will probably not have here an hourly speed exceeding 300 miles. As retardation will affect them equally, their relative speeds will be as 7 : 3 till one overtakes the other and they coalesce. Off Halifax the forced wave will not, under these assumed conditions, have yet overtaken the free wave which in any case has here more room to spread out, and so, such a high tide will not result as when the two arrive together on the Maine coast, which will arrest their onward progress and deflect the enormous volume of water into the comparatively contracted Bay of Fundy. The lunar tide will have overtaken the anti-lunar derived tide, and a greater elevation must result than when their two smaller companions meet in the same place 12 hours later, as observation shows to be the case.

The derived wave for north-west Europe starts at the same time and has about the same distance to go to the north of Ireland, and some 300 miles less to the parallel of Ushant. With a similar initial velocity I have shown that the speed must be materially reduced by shallow water and obstructions, and I question whether it would average 300 miles per hour, which would bring it off the entrance to the English Channel in 25 hours, or when the moon is again at her inferior transit, and this, the higher of the two southern waves, would meet the smaller of the true tides of the Northern Hemisphere. Twelve hours later the smaller tide from the south would arrive with the lunar tide, and thus we get the equality of heights characteristic of these tides. From the nature of the obstructions and the position of the co-tidal lines, I think it probable that the derived tide does not average more than 270 or 280 miles per hour, and that it arrives 2 or 3 hours after the moon crosses the meridian. It only requires a mere alteration in detail to show the same results when the moon has high southern declination.

This brief sketch of the nature of Atlantic tides is necessarily incomplete, and more or less speculative from want of data to prove the conclusions that I hope I have at least shown plausible reasons for. Nowhere outside the Hydrographic Office can there be sufficient data, or a sufficient staff to deal with the exhaustive analysis necessary to track the volume, course and speed of the free wave in the different regions of the North and South Atlantic and estimate the amount of retardation due to the different influences. A fairly close estimate of its ultimate effect on the American coast might, I think, be arrived at by comparing the tides

with those of similar parallels in the South Atlantic and Pacific, on the shores of Argentina, Patagonia and New Zealand, where the only interference with the progress of the tidal wave is the retardation caused by the slope of the sea-floor and the land itself. The volume and elevation of the true tide ought to be calculable. Every sea, whatever its size may be, must have a tide of this nature, even though it may be too small to be capable of being observed or measured.

There is a similar but smaller (because of its latitude and distance from the apex of the cone) derived tide round Cape Horn, which has been principally observed along the west coast of Patagonia and southern part of Chili. Future tidal research may reveal the fact that it has an appreciable effect upon the tides of the islands in the Pacific.

Small derived waves, too, must be generated off the south point of New Zealand and south-west of Australia, but as the land is not continuous to the northward, their effects would be modified and perhaps localized by a corresponding but greater elevation from the wave passing north of the island. Wherever the land arrests a portion of the true tide wave, the unobstructed section must raise the level and generate a derived wave, however small or negligible its effect may be.

That these derived waves interfere with the working of our theory in nowise invalidates or even impugns it. When the water surface in one region is raised by obstruction above that of the other seas in free communication with the elevation, the laws of gravity at once come into operation to restore the level, just as certainly as the water of a river must flow from its source to the sea. Why, in opposition to the case of the river, Nature employs wave motion in the open sea, I am unable to determine, except that her laws are invariably adjusted in the most simple and suitable manner to carry out her requirements, and, I might add, apparently to interfere as little as possible with those of mankind. The volume of water required to produce equilibrium or restore the level could not possibly be transferred in the time, as a current from the region of the Cape to the North Atlantic, or if it was no vessel could live on the face of this ocean. Everything in its path would be swept before it. The deep water permits a speed for a free wave from one to five hundred times greater than that of any currents ever observed in the ocean, or even in narrow channels. The wave passes under the vessel without creating the slightest disturbance, or giving any indication to those on board that they are a few feet farther from the earth's centre than they were some hours earlier and will be some hours later. In all these cases Nature chooses the most simple and effective method, and when friction of the sea-floor has increased beyond a point through diminishing depth, the wave is degraded into a current whose velocity may be increased as in a river, by contracted channels or neighbouring depressions.

The derived wave no more vitiates our theory than the land which produced it by obstructing the passage of a section of the tidal wave, that would have had a free run on the ideal world. If we would understand how actual tides are produced, it is equally important to have a true theory for the ideal world and form a just estimate of all the different interferences that will come into play when we apply it to the several localities on our own globe. The derived wave is not the least important of these interferences, which modify the effects of the tide-generating

forces and cause variations from what would be times of H.W. on the ideal world and perhaps considerable changes in the rise and fall.

Professor Tait tells us that in wave motion it is energy which passes and not matter, whilst currents on the other hand imply the passage of matter associated with energy, and that the subject is one which, except in a few very simple or very special cases, has as yet been treated only by approximation, even when the most formidable processes of modern mathematics have been employed. I hope that my description is sufficiently accurate and practical to enable the reader to understand the production of tides.

CHAPTER VII.*

ALTHOUGH the cause of tides has been a subject of speculation from the earliest times, Sir Isaac Newton was the first to evolve a theory worthy of the name. It was a direct result of his discovery of Universal Gravitation, and must have been in the first instance mainly, if not wholly, statical. A theory to be of any practical use in explaining natural phenomena must bear some sensible resemblance to observed facts, and the only available tides of which there was any record in Newton's time seemed to contradict the Equilibrium Theory, which was amongst the first results of the great philosopher's epoch-making discovery.

Newton's effort to reconcile theory with observation led to the 18th and 19th corollaries, Prop. 66, Book I. of the *Principia*, which I have already shown, and are now admitted to be untenable. This introduction of dynamics into the problem, led Laplace in the following century to discard the statical element altogether, and promulgate the dynamical theory, which has ever since been the received theory of the world.

Sir George Airy, a great mathematician and Astronomer Royal, described the Equilibrium Theory as "one of the most contemptible theories ever applied to explain a collection of important physical facts," and "as entirely false in principles and entirely inapplicable in results," but I hope to show that it was only because he misinterpreted it, that he pronounced this scathing condemnation. The mathematical world then believed that Laplace's theory would explain everything, but so far from this being so, Nature contradicts it at every step, and the greatest tidal expert of the day has had to resuscitate the Equilibrium Theory up to a point to help him out of difficulties that Nature puts in the way of the received theory. Even then he has to lament that both "theories must be abandoned as satisfactory explanations of the true conditions of affairs," and the tidal experts trust to the analysis of actual tides, which they fit in as best they can with theory. I will now endeavour to make it clear to the reader that the Dynamical Theory is false in principle, and that the Equilibrium Theory correctly interpreted is capable of explaining the phenomena of the tides on the ideal world assumed by Laplace (one completely covered with water of uniform depth), and on our own globe as far as obstructions will permit. For simplicity I will deal only with the lunar tides, but the sun produces tides in exactly the same manner, which are easily combined with those formed by the moon.

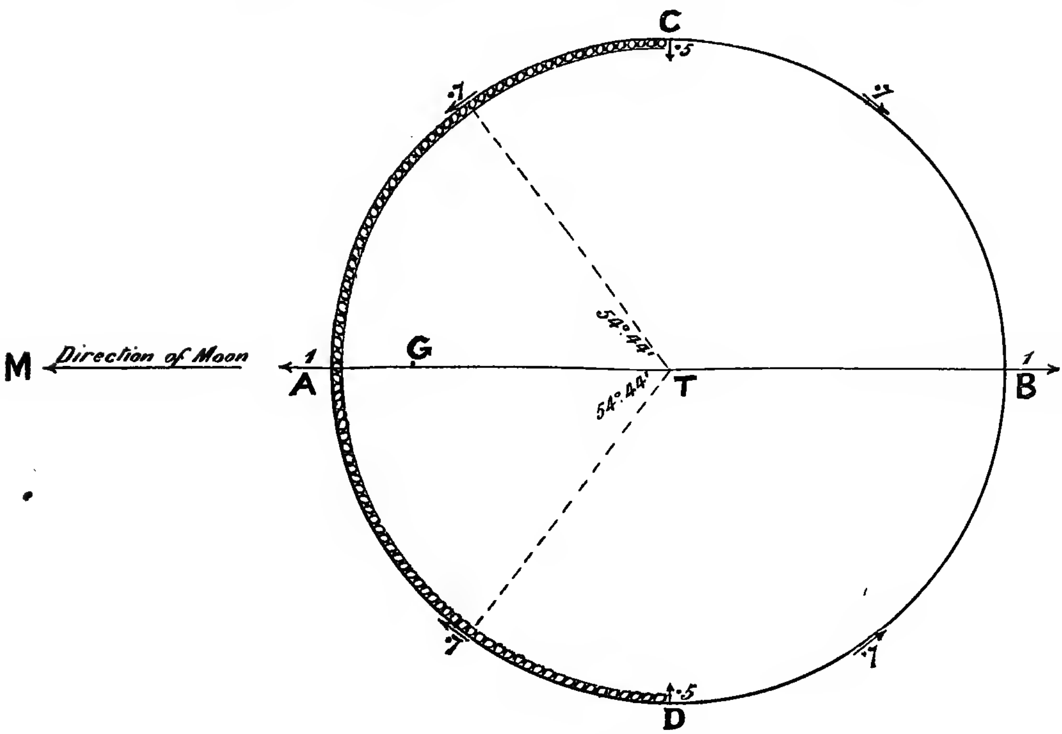
The Professor already quoted describes tide as "a rising and falling of the water of the ocean, caused by the attraction of the sun and moon." I accept that definition, merely remarking for the benefit of the reader that it is not the total attraction that raises the tide, but the difference between the attraction on the particles composing the earth. The total attraction of all the particles in the moon may be supposed to be concentrated in

* Read at the Royal Geographical Society of Australasia, Queensland, Sept 23, 1909

her centre, and the attraction on each particle of the earth varies inversely as the square of its distance from this centre. Of course the earth similarly attracts the moon, but as we are not dealing with moon tides, that does not affect our present subject, except that this mutual attraction or centripetal force would bring the two bodies together if it was not counteracted by another force, which must necessarily be equal to it on the whole, and on the average. This is the centrifugal force of revolution, and it differs from the centripetal force in that it is the same for every particle of the earth, and herein lies the sole cause of the tides which seamen utilize, and mankind in general receive so much benefit from.

DIAGRAM X.

To illustrate how the Differential Attraction of the Moon produces the Tidal Cone.



EXPLANATION OF DIAGRAM.

The circle is a section of the earth, with the point A vertically under the moon. The earth's gravity attracts every point equally towards T.

The moon is 60 radii of the earth, distant from T in direction M.

G is the common centre of gravity, about which they both revolve.

On either side of A is shown a typical row of particles, of which there are an infinite number of rows, all radiating from A.

The earth and moon are kept from separating by their mutual attraction or centripetal force, which is exactly balanced by the centrifugal force of revolution.

Whilst these two forces are equal on the whole, and on the average, they are not the same for every particle of the earth.

The centrifugal force has the same magnitude and direction for each particle of the earth, and acts in parallel lines, either along A B or parallel to it.

The lines of centripetal force being directed to the moon's centre converge slightly, and the attraction varies inversely as the square of the distance of each particle from that centre.

Whilst these two forces must be equal, and balance one another at T (and practically all along the line C T D), it is quite evident that A, being so much nearer the moon, centripetal will be stronger there than centrifugal force, and that at B centrifugal force will have the greater intensity.

These "overbalances," as they are called, are the tide-raising forces, or tide-generating forces.

At A the tide raising force is a maximum, and acting at right angles to the earth's surface in opposition to her gravity.

It can be easily demonstrated that at C and D the force will be just half what it is at A and normal to the earth's surface, but acting inwards.

At 54° 44′ from A the force is seven-tenths of the maximum, and acting wholly tangentially.

At all other points it has intermediate values, and acts more or less obliquely, but can be resolved into rectangular components, acting normally and tangentially.

Between C and 54° 44′, it acts partly inwards and partly tangentially. Thence to A it acts tangentially and outwards.

The attraction towards M is greatest on the particles at A. As the distance from A increases, both the total attraction and its vertical component diminish, but simultaneously the tangential pressure towards A increases till at 45° it is a maximum and at 54° 44′, the circle of mean level, it monopolizes the whole tidal force. Then the downward pressure assisting the earth's gravity begins, which becomes a maximum at C and D where the tangential component again vanishes.

As the moon's influence is thus to raise the water at A by counteracting the earth's gravity, and to lower it at C and D by assisting the pressure of the earth's gravity, and as from A to both C and D her attraction gradually decreases its effect in reducing the pull of the earth's own gravity, and so produces the tangential pressure towards A, it must be evident that the whole tendency is to raise a cone of water, the apex of which will be at A, where all the pressures meet. The tangential pressure is increased by the convergence of the lines of centripetal force. The particles press one against the other, and there is no necessity for any surface current as required by the dynamical theory.

The overbalance of centrifugal force produces similarly another cone at B, but it is slightly smaller, because the tide-raising force varies inversely as the cube of the moon's distance.

To get a clear idea of the action of these forces, let us assume for the present that the earth is non-rotating, and in the annexed diagram let the circle C A D B represent a section of the earth of which T is the centre, and A the point under the moon. Then every particle on the circumference (assuming the earth to be a sphere) will be attracted equally by the earth's gravity towards T. The moon being 30 diameters of the earth distant, her attraction at C D and T will be practically the same and equal to her average attraction, which exactly balances centrifugal force. It will be evident that at A the moon's attraction will be a maximum, and that its whole effect will be expended in diminishing the attraction towards T, and there will be an overbalance of centripetal force in the direction of the moon. As we move round the circumference from A towards C and D, the moon's attraction decreases in the ratio of the inverse square of her distance, which is equivalent to an increase in the pressure towards T, and this squeeze produces the lunar cone. Again at B it is evident that the moon's attraction is a minimum, and there will be a similar overbalance of centrifugal force which forms the anti-lunar cone. This is how we contend the tidal cones are generated and equilibrium maintained by differential pressure which acts instantaneously. Even with rotation in abeyance these two cones would travel round the earth in company with the moon once in a lunation, and they account for the whole tidal effect of attraction and revolution. If now we start the earth rotating no more tides will be raised, because the force generated being centrifugal from the earth's centre is not tidal, and only creates a permanent bulge, or lengthening

of diameters round the equatorial regions. Rotation has, however, a marked effect in multiplying the number of tides in a given time, by bringing the different meridians in turn into the already formed cones. The earth in fact rotates through the tide wave, *i.e.*, through the ellipsoidal form taken by the ocean under the influence of the tide-generating forces just described.

These forces are all sufficient to account for tides on the ideal world of Laplace, and on our own globe where there is a free passage for the tidal wave, but the experts of the past were misled first by watching the tides of the English Channel (which are so anomalous that they come in from the westward instead of following the moon) where obstructions create rapid streams, and gave the idea that equilibrium could only be produced by surface currents. This again in turn led to mixing and confusing revolution with rotation, and thence to the dynamical theory, where the tidal wave being unable to keep pace with the moon drops back to quadrature. The wave was originally a free wave, whose speed is regulated by the depth of water. The ocean depths only permitting a speed of about 500 miles an hour, whilst the moon travels over the equatorial regions at double this velocity, the luminary outstripped the wave which then on dynamical principles became inverted. The forced oscillations of a pendulum are requisitioned to explain the inversion, but the analogy is hopelessly inadequate and misleading. The pendulum is inverted but the tide is only semi-inverted. If it were completely inverted the lunar and anti-lunar cones would exchange places, and nobody would be the wiser. But (except for the vertical rise and fall), we dispute that there is any analogy between the motion of a pendulum which swings to and fro, and that of the tide-wave, travelling continuously in one direction —more like the hand of a clock than the pendulum which works it.

I think that I have probably said enough to show both why the cones should be in conjunction (in line with the moon), and why they could not be in quadrature on the ideal world, but let us consider for a moment what the effect would be if they found themselves in that position, and what force would be available to keep them there, because whatever the position is, they must travel 1,000 miles an hour in the equatorial regions, to keep pace with the moon as observation shows they do.

In dealing with the tidal force it is usual to resolve it into its two rectangular components, the one normal or perpendicular to the earth's surface, and the other at right angles to this or tangential. Now, it is quite obvious that at A there is no tangential component, and that the whole force is normal and acting outwards. As we move away from A the normal component decreases and the tangential infinitesimal at first grows till at a point nearer quadrature than conjunction it monopolizes the whole force. After that point is passed it decreases, and the normal component reappears increasing gradually, till it again represents the whole force in quadrature. Now, whilst its value and effect are not so obvious to the non-mathematical reader as in conjunction, it is easily demonstrated that in quadrature where the tangential component is zero, the normal component acts inwards towards T, with exactly half the intensity it had at A. Thus the whole tidal force in quadrature is exerted to depress the water surface, and there is no tangential component to drag the wave crest along as required by the dynamical theory.

In previous chapters, after showing how the tide-generating forces work, I described the principal interferences on our globe with the pure theory that would obtain on the ideal tidal world of Laplace, and showed how diurnal inequality was incompatible with the dynamical principles of that great mathematician, because if the tidal cones were in quadrature they must remain on the equator, whether the moon is over it or the 29th parallel of latitude. The moon herself is a mute witness that Nature forms the cones under the tide-producing luminary, the bulge in her equatorial regions, which before it solidified was a molten lava tide, being on the side next the earth that produced it.

Dealing as before with the lunar tides only, I will endeavour to picture the motion of the tidal cones as they would appear to an observer who could take up a sufficiently distant point of observation in the direction of the moon. If the moon remained over the equator, the tidal cone would travel round the ideal world beneath the observer with the crest mid-way between the poles. But the moon moves north and south of the equator like the sun, only much more rapidly than the latter, and instead of always just reaching the tropic, she sometimes stops short at the 18th parallel before turning back towards the equator, and in other years attains the parallel of 29°.

If to-day the moon is over the equator, our observer in the heavens will see the summit of the tidal cone on the equator, but to-morrow it will have advanced 5° or 6° towards the pole, keeping pace with the moon. The next day the moon and the cone making a little less northing will be still farther from the equator and nearer the pole, and day by day as the earth rotates under the moon, the line joining the centres of the earth and moon passes through the apex of the tidal cone, which is farther from the equator and nearer the pole than the day before, although the rate at which it approaches the pole decreases. Our observer then from his post of vantage will see that the apex of the tidal cone describes a decreasing spiral from the equator towards the pole, and after about seven whorls, which it takes a week to complete, he will see the cone commence an increasing spiral towards the equator, which it will approach just as before it receded from it, the convolutions of the two spirals crossing one another as right and left-handed spiral springs would do if placed one inside the other. The cone having reached the equator, our observer would see a similar pair of spirals traced by it on the surface of the globe towards and from the other pole, all four being completed in a lunar month. The cone he has been watching is the apex of the lunar tide, which always faces the moon.

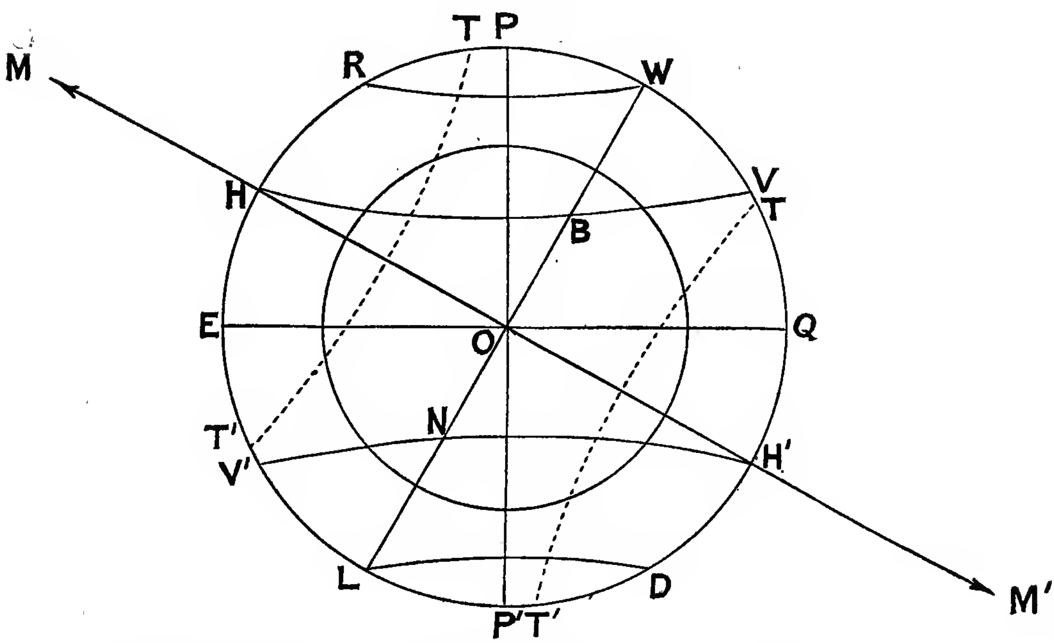
Diametrically through the earth on the side remote from the moon the anti-lunar cone travels round in exactly the same manner as the one I have described, the only difference being that it is slightly smaller, because the overbalance of force is rather less there than on the side next the moon. These are the only two tides that the moon can and does raise, although variations in them are produced by changes of declination and distance of the moon, and the interferences already described in former chapters.

Midway between these two cones lies a belt of lowest water or greatest pressure, because there the moon's attraction is acting so as to assist terrestrial gravity in depressing the surface level. The variation in the heights of successive high waters is often spoken of as a diurnal tide,

as if it was a separate entity instead of only a difference in two consecutive semi-diurnal tides. I will now explain a little more fully how diurnal difference, or inequality, is produced and give an example from actual observation, proving the accuracy of our views.

In Diagram XI. let EQ be the earth's equator, PP′ the axis of rotation, and HM the moon's direction. Then H will represent the apex of the lunar tide, and H′ that of the anti-lunar tide, whilst LW will represent the middle of the band of depressed water, any place situated on which will be in lowest water. At V and V′ there will be at the same moment a moderate high water, but not nearly so high a tide as at H and H′, it being understood, too, that the tide at H′ will not be quite so high as that at H. As the earth rotates on PP′, every place on the parallels HV and H′V′ will, during the lunar day, occupy successively the positions with respect to the moon held in the diagram by H and H′ respectively. When any place is at H or H′ it is in highest water. When it is crossing LW, or the continuation of the hemi-circle WL on the side of the earth invisible in the diagram, it is in absolutely lowest water. When the place

DIAGRAM XI.



To illustrate the action of Tide-generating force of Moon on Ideal World; and as far as obstructions will permit on our Actual World. The Sun's force is similar but less.

The outer circle is a section of the Earth of which O is the centre; P and P′ are the Poles, and PP′ the axis of rotation.

EQ is the equator, M (or M′) is the direction of the Moon with extreme declination, 30 diameters of the Earth distant from O, the centre.

The apices of the Tidal Cones are at H and H′ and the parallels HV and H′V′ rotate through them. The dotted circles TT′ are those of mean level 54° 44′ or 3284 nautical miles from H and H′ and where the tidal force is wholly tangential. LW is the belt of lowest water. RW and LD are parallels of single day tides. If we remove the Moon from the plane of the paper and bring her vertically over O, the inner circle represents that of mean level, and the outer circle becomes that of lowest water, as LW was in the first case.

has rotated from H or H′ to V or V′, it will be in modified high water. It will thus, during the lunar day, have passed twice through low water, once through highest water, and once through the modified high water. For any place on the equator there will be no diurnal difference, except the very slight one owing to the high water at H′ not being quite so high as that at H, and should the moon be over the equator, and so EH, or the moon's declination disappear, it is evident that diurnal inequality will practically vanish at all places. The two semi-diurnal tides will be equal all over the world, or the difference will be so small (being merely that due to the tide opposite the moon through the centre of the earth being slightly less than that under the moon) that it may be neglected.

On the other hand, it is plain that while the moon's declination is as given in the diagram, the elevation of the water at H and V cannot be the same, nor can the elevation at V′ be equal to that at H′. It is also evident that, since the tide at H is higher than that at H′, and consequently the tide at V′ higher than that at V, the diurnal difference at H and V will be greater than that on the parallel H′V′, and thus it is plain that diurnal inequality is most marked when the latitude of the place on a true-tide bearing sea and the declination of the moon are of the same denomination.

To make this clear, suppose the elevation above mean level at H to be 42 inches, then at H′ it will be 38 inches. If, now, the rise at V′ situated on the slope of the higher tidal crest is, say, 18 inches, that at V on the slant side of the smaller cone will be but 16 inches. The diurnal difference then on the parallel under the moon is $42 - 16 = 26$ inches, or 30 per cent. greater than that in the other hemisphere due to the anti-lunar tide, which is $38 - 18 = 20$ inches.

This theoretic result was amply confirmed by the tides of Hobart, where, in 1893, Captain Goalen, R.N., found that the smaller of the two semi-diurnal tides disappeared when the moon had high southern declination. A fortnight later, when the moon had extreme northern declination, the same tide was very much reduced, but was still appreciable. The tide at Hobart is a small one. When declination is great and south, the lesser of the two daily tides fails to get up the deep bay at the head of which the port is located. Had it been nearer the open coast, the same difference would doubtless have resulted, but it might not so readily have caught the eye as the vanishing tide of Hobart, which is an exact corroboration of the principle I have just explained.

As diurnal inequality is thus dependent upon declination, it is clear that it will be greater at any given place during years when the moon reaches the parallel of 29°, than in others when she only moves 17° or 18° each side of the equator, and this has doubtless led to apparent inconsistencies.

Suppose, for instance, that a series of measurements of the tides were made in Sydney Harbour when the moon's declination reached 29°, and again a few years later, when it never exceeded 18°. The diurnal difference of the first set of observations would be much more marked than in the later survey, and if the cause of the discrepancy did not appear, it might be thought that one set was inaccurate. Again, should the measurements be made at Sydney during a period of maximum declination, and a similar set at another port about the same parallel and in the same ocean (say Parengarenga Harbour, New

Zealand) during a period of minimum declination, a very different set of phenomena would be recorded in each case, and there would be a supposed inconsistency to unravel.

Dynamical theorists agree that diurnal inequality depends upon declination, but with the tidal cones in quadrature as they place them, they would remain constantly over the equator, and could, as I have shown, only produce the slight inequality due to the difference in the height of the two cones.

Another interesting example of the influence of declination is afforded by a peculiarity of the tides of Hong-Kong, brought under our notice by a naval officer serving on that station. The "age of the tide" (the number of days after full and change of the highest tide) was there a variable quantity and upset all known rules, the highest spring tides occurring sometimes at full or change of the moon, and at other times as much as three days later. At Albany Island in the same ocean, it was sometimes a minus quantity, the highest water preceding full or change by perhaps two or more days, and at other times following it.

These irregularities, inexplicable by the dynamical theory, are on our principles, necessary results of the tidal cone moving north and south with the moon. Hong-Kong lies between latitude 22° and 23° N. About the equinoxes the moon is full or new near the equator, and three or four days later she is nearly over the parallel of Hong-Kong. For example, in April, 1898, full moon occurred on the 6th. The moon's declination on that day was 9° north. The apex of the tidal cone passed on 6th April over places 9° from the equator. On the next day declination was 5° greater and the cone 5° farther north, and so on to 9th April, when the moon was 23° from the equator, and Hong-Kong lay in the path of the very apex of the tide. The tide of the 9th was not so high under the moon as the tide of the 6th, when the apex of the cone was nearly 1000 miles away, whereas on the 9th it passed right over Hong-Kong, and so a delay of three days in the time of the highest water took place. The tide of Hong-Kong gained more from the approach of the apex of the tide than it lost by the decline of the tide towards neap. On 10th April the moon was still farther north, and Hong-Kong lay to the south of the tidal summit. The decline towards neap was then assisted by the change in the distance of the highest point, and the tide did not rise to the level of the day before.

Had the moon been over Hong-Kong when she was full and moving south, the highest tide would have occurred on that day. †In June of this present year it will be full moon on the 4th, and new moon on the 18th in Eastern waters. At full moon the anti-lunar tidal cone will be nearly over Hong-Kong, as will be also the solar tidal cone. As, however, the latter is nearly stationary in latitude, and the former is moving slowly north, and passes over it again about three days later on its way south, whilst the moon is all the time getting nearer the earth, the highest of three or four high tides will probably be two or three days after full.

At new moon on the 18th the tide will be higher than on subsequent days because, though the moon is moving north, and has to come back over Hong-Kong, she will lose more by her separation in longitude from

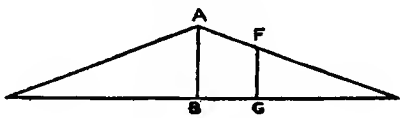
† Written in March, 1909.

the sun and by reason of increasing her distance from the earth, than she will gain by her own verticality.

Under the head of apogee and perigee, the moon's greatest and least distances from the earth are recorded in most almanacs, as well as her declination (corresponding to latitude on the earth) and the hour of her meridian passage. If the moon is within a day or two of perigee at full or change, the decrease in her distance in the next 24 or 48 hours may have as great an effect in keeping up the height of the tidal cone under the moon as the sun's separation from her has in lowering it.

If in Figs. 5 and 6 the upper cone with the greater altitude represents the crest of the lunar tide at full or change, the second cone with a lesser altitude may be taken as representing the same tide two or three days earlier or later, when the apex will be lower, because the sun's influence is oblique to that of the moon. Now, whilst AB is, of course, greater than CD, it is equally evident that CD is greater than FG, which may

Fig. 5.



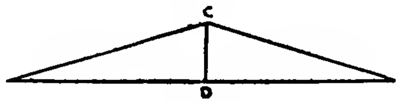


Fig. 6.

be taken to represent the height over Hong-Kong on 6th April. Three days later CD would be over Hong-Kong and produce a higher tide there than when AB measured the rise 1000 miles farther south.

The same figures will do to illustrate the tide at Albany Island, CD representing the apex right over the island two or three days before full moon, and A the summit of the cone on the day of full moon 800 miles farther south, whilst the island on the slant side of the cone will only have an elevation FG above mean level.

Albany Island is in latitude 11° S. On 4th June this year, when the moon will be full, she will be over the twenty-third parallel of south latitude. On 1st June she will be over the twelfth parallel, and so Albany Island will be in the apex of the lunar tide, and will have a higher tide than when the moon is full and crosses that meridian 12° farther south. The crest of the tide is, of course, higher under the moon on the 4th, but on that day Albany Island is 800 miles distant along the slope of its northern shoulder.

Dynamical theorists used to tell us that just as the weather in England is warmer in July than in June, when we have longer days, and the sun higher in the heavens, so the oscillations of the tide go on increasing after full moon and produce the highest tides a day or two later. It is obvious that this explanation is worse than useless in the case of Albany Island, and not because the tide is anomalous, but because it obeys a simple and natural law. An explanation which Nature so emphatically contradicts in the case I have just quoted, is hardly likely to have any value even in more plausible instances. At Albany Island the result

of observation and enquiry supports our theoretical conclusion that the only oscillations in the tidal problem are the vertical rise and fall of water and the passage of the cones north and south of the equator, as they follow the moon's change of declination.

This vertical oscillation is the essential characteristic of wave motion, which distinguishes it absolutely from current, and is the only conceivable explanation that makes it possible to combine the enormous velocity entailed with immunity from destruction to everything in the path of the wave.

The tidal wave travels round the equatorial regions at over 1000 miles an hour. A current with only a fraction of this velocity would sweep everything before it. The dynamical theorists talk of the moon dragging the tidal wave round 90° behind her, where the dragging or tangential force is admitted by all to be zero. The expression is a most misleading one, implying horizontal transference of the water, whereas in wave motion it is the form alone that travels along horizontally, the change in position of the crest being brought about by vertical oscillations of the particles of water. The protuberance rises to form the cone at any particular spot on the earth's surface, because the moon is vertically over it, and terrestrial gravity is most counteracted there. The next moment the protuberance is at the next spot, not because the water previously raised has been dragged forward, but because the former protuberance is sinking and a new one rising.

As the earth rotates under the moon the particles in front of her are always rising vertically in response to her increased attraction; and those to the eastward of her, which she has passed over, sinking vertically because she no longer attracts them so forcibly. At each instant a new set of particles receives the strongest pull of the moon's attraction, and the same applies on the other side of the earth to the particles acted on by the overbalance of centrifugal force. Whilst the wave form thus moves from east to west, there is no horizontal translation of particles of water. To a distant observer, if he could mark the progress of the cone, it might appear that the water was being transferred laterally, but it would be a mere optical illusion, which would be dispelled if he saw the wave meet a floating object, such as a log or a boat. The wave travelling with enormous velocity would leave the boat where it found it. A current, on the other hand (as in a river), would carry the boat with it. Treating the tidal protuberance as a wave moving like a current has been the cause of much misconception in tidal theory.

Another anomaly that we were asked to explain was why the tide at Whampoa dock was 4 feet higher in June than in March, when theory taught us to look for the highest tides at the equinoxes. Such, it is true, is the teaching of the dynamical school, which we cannot subscribe to. We hold, on the contrary, that on an ideal world the tidal cones would always be under and opposite the moon (neglecting for simplicity all consideration of the solar tide), and that on our actual world the same holds good as far as obstructions and interferences permit. Consequently, equinoctial tides are only greatest in the neighbourhood of the equator, and Whampoa dock, being near the tropic of Cancer, will have its greatest tides when the moon is at her nearest to that parallel, and almost as large ones when near Capricorn she produces the anti-lunar cone close to the northern tropic. At the solstices she will have the solar tidal cones close

to her own, or possibly coincident with them, and very high tides must result with large diurnal inequality.

Whilst to avoid complication and simplify the problem for the general reader, I have left the solar tides out of consideration, they are formed by the sun in exactly the same manner as the lunar cones are produced by the moon, the only difference being that they are smaller, because while the sun's attraction is enormously greater than the moon's, the overbalances of force, which are the actual tide raisers are much smaller, owing to the sun being four hundred times more distant than our satellite. When the sun, earth, and moon are all in line, as during an eclipse, the lunar and solar cones are superimposed one upon the other, and *cæteris paribus* produce maximum tides. When the moon is in her first and third quarters, her tidal cones are on a diameter of the earth at right angles to those of the sun, and each pair of cones subtracts from the height of the other, producing neap tides. On other days the height of the tide has an intermediate value, depending on the inclination of the axis of the solar to that of the lunar cones, or approximately on the difference of meridian passage of the tide-producing bodies.

The researches and measurements of Professor Hecker, of Potsdam Observatory, are the strongest confirmation of our theory. The earth tide which he has succeeded in measuring is an equilibrium tide. It must be formed by the differential pressure of gravity caused by the overbalances of centripetal and centrifugal forces. The description of wave motion in the ocean applies equally to it, the particles taking a little over six hours to attain their greatest elevation of about 8 inches, and the same time to sink to the level from which they rose.

That the tide-generating forces should produce dynamical tides in the ocean, and equilibrium tides on dry land, is as inconceivable as that these latter could be formed by surface currents, and so assurance has been made doubly sure.

CHAPTER VIII.*

Twenty-two centuries ago Alexandria was the most famous city in the known world. Founded by order of Alexander the Great, it flourished under the Ptolemies till it had no rival for wealth, commerce, or splendour. It was equally renowned as a seat of learning. Its magnificent museum and library, containing 400,000 volumes, and the facilities granted to foreigners for their use, attracted teachers and students even from Greece, then at the zenith of its fame. Amongst those who found their way to Alexandria, perhaps first to study and afterwards to teach, was Aristarchus of Samos, an eminent mathematician and astronomer. Aristarchus, of course, learnt astronomy according to the ideas then prevalent and accepted. After years of study he felt sure that they were wrong, and wrote a book to prove it and to persuade astronomers that the world rotated on its axis and revolved about the sun, whose distance from it, although great, was very small in comparison with that of the fixed stars.

Unfortunately for Aristarchus, his name and fame were overshadowed by those of perhaps the greatest of ancient mathematicians, Archimedes, who, imbued with the orthodoxy of the day, could not examine the new ideas with an open mind. So complete was the victory of authority over the newly-discovered truth, that the work of Aristarchus perished with him, and we only know of it through the writings of the man who condemned it. Thus the world had to wait nearly 2000 years before Copernicus, Galileo, and Kepler demonstrated the accuracy of the Samian astronomer's assertions, which ought to have found acceptance in his lifetime. Great as was the reputation of Archimedes, he was evidently in this case blinded by prejudice, and the advancement of science was retarded by the very man who should have assisted it, and perhaps thought he was doing so.

Our tidal theory would have met with a similar short shrift from the orthodox authorities, but that we would not accept defeat and condemnation without a shadow of proof, whilst Nature supported us on every side as consistently as she contradicted Laplace. Kepler and Galileo were both persecuted as the reward of their labours. Moxly went to his grave without any acknowledgment from the scientific world. He had, however, the satisfaction of knowing that many high-class mathematicians admitted that they could see nothing wrong in his work, and that we had made shoals of converts amongst navigators and others interested in the subject. Thus it seems probable that the vindication of the modern Aristarchus will not be such a long process as in the case of his ancient prototype.

Two-thirds of a century ago, the most authoritative treatise on tides was probably that in the *Encyclopædia Metropolitana*, by Sir George Airy, a highly distinguished mathematician, and then Astronomer Royal. Whilst he admitted that the Equilibrium Theory had its uses, he condemned it unsparingly as an explanation of tidal phenomena. I have

* Most of this and the following chapter is reprinted from *Proceedings and Transactions of the Royal Geographical Society of Australasia*, Vol. XXV.

already shown strong reasons to doubt his conclusions, and will now by further quotations endeavour to make it clear that he misinterpreted the theory he judged so uncompromisingly, and misread the face of Nature. He says, "Suppose now that the water assumed the form which we have found, and that the earth revolves within its coating of water. This supposition, absurd as it is, is the only one upon which it is possible to apply the Equilibrium Theory." If this was the interpretation of the Equilibrium Theory by the greatest expert of his day, it probably was that of his predecessors, and it was fifty years later when Moxly first pointed out that the supposition formed no part of the theory, and was, on the contrary, in direct opposition to it. The Equilibrium Theory does not postulate an earth, whose solid nucleus revolves within a coating of water, through which the protruding continents sweep at the rate of 1000 miles an hour. It postulates an earth rotating with its coating of water through an ellipsoid form. The ellipsoid is formed by the coating of water itself, the water actually composing the protuberance changing from moment to moment, and therefore not remaining with the moon to be swept through by protruding continents and islands, but sweeping forward with the earth's rotation in company with the continents and islands. It is a state, and not a body that remains with the moon by the Equilibrium Theory; it is a form (or shape), and not a material that is permanent, whereas the statement of the astronomer is that it is the water which at any moment forms the protuberant or ellipsoid form that remains, the solid earth rotating through it. That this fallacy in a standard treatise escaped detection for half a century is sufficient to show how universally it was believed and accepted, and how little chance the Equilibrium Theory had of establishing its claims with the scientific world. Now, the misconception is universally admitted, but full recognition is not yet accorded to the consequences of the discovery, because the dynamical Professors are loth to surrender all belief in the theory they have accepted so long, notwithstanding their own admissions of its shortcomings. Sir George Airy acknowledged its complete failure to explain diurnal inequality in the Pacific Ocean, "where the case possesses considerable analogy to his (Laplace's) assumption," *i.e.*, a sea of equable depth with no land to interfere with the progress of the tidal wave.

Inimical as the supposition I have just dealt with has been to the theory I am advocating, I subsequently discovered in the same treatise a statement that I believe is equally fallacious, and that is fundamental to the dynamical theory. After stating that the theory of Laplace is one of motion, he continues, "A small vertical rise implies large horizontal motion. Suppose in one part (quadrant) the length of the canal is 1000 times the depth, and suppose the water depressed one foot, it is evident that the volume of water (omitting factor of breadth) for which a new place has to be found is = length of canal $\times$ 1 foot = 1000 $\times$ depth $\times$ 1 foot, or depth of canal $\times$ 1000 feet. Consequently, the water at one end, if that at the other remained unmoved horizontally, must have moved 1000 feet, or 1000 times the vertical movement."

I do not think that this statement or conclusion bears any resemblance to the unobstructed tidal movement of the water on the earth's surface, which I will now endeavour to illustrate, even though my analogy be not quite perfect.

Imagine a tube of uniform bore, 6000 miles long, round a quarter of the earth's equator, with each end turned up to a height of 8 feet. Let it be filled with water which stands 4 feet high in each end of the tube. If now, we insert a piston at one end, and force it down to within a foot of the bottom of the tube, the water surface will be depressed 3 feet, and in the other end of the tube it will have risen 3 feet. It is quite obvious that in the horizontal portion of the tube the amount of movement has been the same. Every particle of water in the tube will have moved through the same distance, and the horizontal movement has not exceeded the vertical movement. If we increase the number of tubes sufficiently, we have an approximation to the action of the tidal force, the principal difference being that in the tubes the pressure is uniform and the motion wholly tangential (except of course in the ends),whilst in the case of the tide generating force, the pressure is differential over the spherical surface. This supposed necessity for comparatively enormous horizontal motion, associated with a few feet of vertical rise and fall, seems to have been one of the assumptions which misled Laplace, and stultified in a large measure the result of his investigation. The name of Laplace is one to conjure with in the mathematical world, but the greater his ability, and the sounder his reasoning, the more certain he would be to come to an erroneous conclusion if he started with false premises, as I assume he did from Airy's account of his theory, which still receives official recognition.

The dynamical theory of the tide dies hard, notwithstanding its admitted failure to explain the movement of the waters on the surface of our sphere, and that it covers the globe with anomalies, but I think that the recent discoveries and measurements of Professor Hecker, of Potsdam Observatory, have at last given it the "coup de grace."

Founded originally upon the same fallacy that displaced its predecessor and which assumed that equilibrium could only be produced by surface currents for whose effective action nature refused to provide sufficient time, it has been bolstered up ever since by other fallacies, the help of Newton's theory, and the analysis of actual tides. The impossible currents from east and west and from north and south were still retained, connected in some mysterious way with the dynamical wave, which by the principle of forced vibrations should be inverted, and yet is only semi-inverted to quadrature. In this position the non-existent tangential component of the tide-generating force drags the wave round after the moon. We would then have the lunar tidal cones always on the equator, where they could produce no diurnal inequality (except the minute difference due to parallax), and on a diameter of the earth perpendicular to the moon's direction, instead of as in the equilibrium theory at the extremities of the diameter which points to the moon.

Such, briefly, is the dynamical theory of Laplace, which supplanted the equilibrium theory of the greatest natural philosopher that the world has ever seen, when the latter, and after him Daniel Bernoulli, had altered it to produce results more in accordance with the only tides they had to compare it with, those of the English Channel. Now for hours before the moon reaches the meridian in this locality she has been passing over dry land, where although producing the earth tides measured by the German savant, it would indeed be astonishing if she could bring the ocean water with her to form regular tides along the coasts of Western

Europe, as she would do on the ideal world (one covered completely with water) and actually does in the Southern Ocean.

The apices of the equilibrium cones are under the moon, and diametrically through the earth on the side remote from her. The water is raised under the moon because there she produces her greatest effect in counteracting the earth's gravity, which attracts every particle on the surface of our globe equally towards the centre (assuming the earth to be a sphere). If we imagine a series of circles to be drawn round the apex of the cone similar to parallels of latitude round the pole, every point in any one circle will be the same distance from the moon, but each circle as we leave the apex will be farther from her, and attraction on the particles composing it will decrease in the ratio of the inverse square of the moon's distance. This gradual decrease in the moon's attraction or centripetal force is equivalent to an increase in the pressure of terrestrial gravity, and is the cause of the formation and maintenance of the cone under the moon.

The centrifugal force developed by the earth in its revolution with the moon round their common centre of gravity counteracts the centripetal force, and keeps them from approaching each other. Whilst it is obvious that the two forces must be equal on the whole and on the average, centrifugal force, unlike the other, is the same for every particle in the earth. Consequently, while near the earth's centre they exactly balance each other, it is clear that on the side next the moon centripetal force must be stronger, and on the remote side weaker, than centrifugal force. The excess of force on each side, the "overbalances," as they are called, create the tidal cones, one, as I have already described it, towards the moon, and the other in an exactly similar manner away from her on the opposite side of the earth, the only difference being that the latter is slightly smaller owing to decreased parallax. If the earth were non-rotating these cones, which are at the extremities of the major axis of the ellipsoid of revolution, would travel round with the moon, producing only two tides in a lunation. The moon forms the ellipsoid by causing differential pressure on the watery coating surrounding the ideal world, the particles forming the protuberances changing from moment to moment so as to keep the major axis pointing to our satellite. The only deviation from permanency is caused by variation in her distance. Rotation raises no tide, although it creates a protuberance that lengthens all the equatorial diameters by the same amount and makes no difference in level along any particular parallel of latitude; but as the earth rotates through the ellipsoid the number of tides are multiplied by the frequency with which each meridian is brought to coincide with the apices of the already formed cones.

Unlike the currents of the dynamical school, which require indefinite time, the pressure I have described can act as instantaneously as atmospheric pressure in the cistern of a barometer, or on the surface of the ocean itself, when it reduces the height of the tide.

More than one of our critics have asserted that they do not understand our claim that Moxly was the first to suggest pressure instead of current, and that mathematicians have always been accustomed to work with pressure when discussing hydrostatical and hydrodynamical problems. I think it will probably be a sufficient, although by no means the only refutation I could advance of this statement, if I refer the reader

to the work entitled *Tides and Kindred Phenomena*, by the greatest dynamical expert of the day, and published since this controversy commenced. In it he will seek in vain for any suggestion of pressure. He will read that equilibrium could only be produced by currents flowing "down hill," till counteracted by a tendency to flow "up hill," and that "with the earth spinning at its actual rate, and the moon revolving as in Nature, the form of equilibrium can never be attained by the ocean." This was why the equilibrium was abandoned for the dynamical theory, but any allusion to pressure is still conspicuous by its absence, and currents from every point of the compass flow to and fro and oscillate to form the dynamical wave, creating eddies and vortices (p. 159–161).

Now, the same forces are operating to form the earth waves measured by Professor Hecker, but he measured no surface currents and observed no vortices. The tides he noted are obviously due to pressure.

I have shown in the third chapter that the description given of the dynamical theory in *Tides and Kindred Phenomena* does not agree with that put forward a few years earlier by another professor in *Time and Tide*, whilst neither is in accordance with a third interpretation sent to Moxly a couple of years ago by a professor of his own University to combat our views. In it the centrifugal force of revolution without which the earth and moon would inevitably collide, and which is the cause of the anti-lunar tide, is omitted altogether, and whilst pressure is mentioned in a way that we doubt would be effective in tide raising, it certainly is not introduced as the prime cause of tides on our world, and the only cause of them on the ideal world of Laplace, with every obstruction, such even as wind removed. Pressure may have been (and probably was) Newton's original conception of tide generation before he was misled by the tidal streams of the Channel, but it was not thus that he gave his theory to the world, nor has any writer on the tides before Moxly suggested it.

It is true that of comparatively recent years pressure seems to have been associated with the idea of tides in the solid crust of the earth, an with the figure of the earth itself, and so it is all the more extraordinary that when the dynamical theory proved so unsatisfactory none of the experts should have thought of applying the same principles to the tides of the sea. Some thirty years ago, the late Lord Kelvin, for whose scientific ability and inventive genius, I in common with all navigators have the greatest admiration and respect, predicted these earth tides and the effect of the moon's attraction on the shape of the earth. He demolished the argument of some geologists that the earth was hollow and filled with molten lava, by showing that even if the crust was 50 miles thick it would have to be scores of times more rigid than steel not to take the equilibrium form, *i.e.*, the earth and water would yield to the tidal influence, together as a whole, and there would be no relative displacement of the water to give us the phenomena of tides. He estimated that the rigidity of the earth was probably the same as that of a solid globe of steel when it would still yield sufficiently to reduce the ocean tides to only two-thirds of what they would be if the earth was perfectly rigid.

I understand that Hecker's measurements confirm the accuracy of this estimate, and the foresight of its author. Kelvin, on whose shoulders was cast the mantle of Newton, was, however, a very busy man, and had not time to go to the root of every subject himself, and so probably owing to the pressure of other work, he did not question the conclusions of his

great predecessor Laplace, which he used as the basis of his speculations on the tidal problem of the ocean.

I have been told by a very clever mathematician that the equilibrium theory of Sir Isaac Newton and the dynamical theory of Laplace "refer to ideal tidal problems, neither of which can be applied to the actual circumstances of our globe." I was, of course, aware of the first half of this statement, and think that the second portion requires considerable qualification. Each theory was in turn evolved for an ideal globe as a stepping stone towards understanding the action and result of the tide-generating forces on the world in which we live. If we form an erroneous estimate of the action of the tide-generating forces on the ideal world (one completely covered with water of a uniform depth), this must inevitably mislead when the tidal expert endeavours to combine it with the probable effect of obstructions on our globe, and may make these latter appear to act in a manner exactly the reverse of reality. On the other hand, if we know certainly how the tide-raising forces would play their parts on the ideal world and can form a fairly accurate idea of the effects of obstructions in the shape of land and shallowing sea floors on our actual world, we can combine the two to make very close predictions* ; or if the effect of obstructions is the unknown quantity, we ought to be able to get somewhere near it by comparing actual tides with the theoretical ones.

Let us consider for a moment an intermediate condition, and assume that all the land on the surface of the globe has been removed except the island continent of Australia, and that the remainder of the earth is covered with water to the most suitable depth for the dynamical wave. Suppose the moon with 25° southern declination to be over the east coast of Australia. It will take her about three hours to reach the west coast, and she will pass over the centre of the continent. Vertically under her during the whole of this time the land will attain its greatest elevation, the particles rising slowly as she approaches their zenith and sinking similarly after she has passed. Now, is it reasonable to suppose that while the moon is elevating the land under her, she is by means of a totally different process raising the water of the ocean on the meridian 90°, or six hours to the eastward, and the same to the westward ? If so, when she had travelled another three hours to the westward her tidal force would be acting vertically downwards with maximum depressing effect on the east coast of Australia, while piling up the water of the adjacent ocean to its greatest tidal elevation. I do not think it can be necessary to employ the higher mathematics to prove the absurdity of such a supposition.

But it is not only to the vertical movement of the solid earth that I can appeal for support of our views, because they are also corroborated by atmospheric tides. Between the years 1840 and 1844 a long series of observations in the island of St. Helena by Captain Lefroy, R.A.,† and Captain Smythe, R.A., demonstrated conclusively that there was an atmospheric tide, with the crest under the moon, and this was confirmed by subsequent observations during the two following years, which were examined and verified by Colonel Sabine; and analysis showed that it was greater at perigee than at apogee, as, of course, it should

* *i.e.*, when not interfered with by abnormal atmospheric conditions.

† Afterwards Sir Henry Lefroy, Governor of Tasmania, 1880.

be theoretically. The height of the tide on the ideal world, for an ocean five miles deep, has, I believe, been calculated by experts to be between 3 and 4 feet. Taking it as $3\frac{1}{2}$ feet, the height and mass of the water raised will be to the depth and mass of the water below it as 42 inches are to five miles. That is, the weight of water raised will be, to that below it, as 1 is to 7543. If now, we take the average weight of the atmosphere, as measured by the barometer, to be equal to $29\frac{1}{2}$ inches of mercury, the weight of the aerial wave can be obtained by simple proportion. As $7543 : 1 :: 29\frac{1}{2} :$ weight of the elevated cone of air $= {\cdot}00391$ inches. Whilst this is but a rough approximation, it is probably not very far out, and is given to show that the tide found by Captain Lefroy, which was only ·0039 inches, is sufficient to establish beyond doubt the fact that there are vertical oscillations in the atmosphere similar to those which affect the water of the ocean. Where the producing cause is the same, and the magnitudes proportional, it is surely highly improbable that there will be any material difference in the position of the tidal crests. In this case the atmosphere yields more easily than the ocean, but, on the other hand, the earth is more rigid, and yet we find the same result. The author of *Tides and Kindred Phenomena* tells us that both the equilibrium and the dynamical theories "must be abandoned as satisfactory explanations of the true conditions of affairs." With that statement I am in fullest accord if (as no doubt he does) he means the equilibrium theory, as interpreted by himself, Sir George Airy, etc. Putting current in the place of pressure, and confusing it with wave motion, substituting rotation for revolution, and treating them as if they were synonymous, rendered Newton's theory abortive from the first, and would have destroyed the dynamical theory even if its conception had been sound.

The new theory, where the same pressure that Lord Kelvin showed would, if the earth were hollow, keep it in a continual state of hydrostatic equilibrium, and that raises earth tides and atmospheric tides under the moon, is the prime source of tide generation, would explain everything on the ideal world, and removes at first sight the great bulk of the so-called anomalies on our globe, and will probably account for the remainder, when the special conditions in each case can be studied closely enough to account for the effect of local obstructions. I have proved this by numerous examples, and shown that diurnal inequality is absolutely incompatible with the dynamical theory, and can only be explained by an equilibrium diagram, which the orthodox tidal experts use, although, according to their teaching, it represents nothing in Nature.

In the last chapter I gave a more detailed account of diurnal inequality with many illustrations of tides conforming to our theory that were previously inexplicable. These are now sufficiently numerous to preclude the possibility of mere coincidence, and are moreover so simple and obviously correct when the true theory is once grasped, as to leave no doubt in any unprejudiced mind. I will, however, give a few more examples:

The Tide Tables for the Coast of California and the Admiralty Tide Tables insert this note, viz., "The tides on these coasts are of so complicated a character, that the following general explanation is considered necessary: There are generally in each 24 hours, or rather lunar day of 24 hours 50 minutes, two high and two low waters, which are unequal in height, and in time, in proportion to the moon's

declination differing most from each other when the moon's declination is greatest, and least when the moon is near the equator. The high and low waters generally follow each other thus. Starting from the lowest low water, the tide rises to the lower of the two high waters (sometimes improperly called half-tide), then falls slightly to a low water (which is sometimes merely indicated by a long stand), then rises to the highest high water, whence it falls again to the lowest low water."

The reason of this sequence is readily understood on our principles by referring to a map or chart of the world, or to Diagram XI., in which HV represents a parallel of latitude passing through the region of these complicated tides.

Leaving the sun out for the present, and remembering that his influence will, as his declination increases, accentuate the peculiarities noted, let us assume the moon to have extreme northern declination, and that H′HM represents her direction. PP′ is the earth's axis of rotation, EQ the equator, and LW the circle of greatest depression. The Pacific Ocean has here a breadth of 120° of longitude; the remaining 240° may be treated as land, the Atlantic having, as far as these tides are concerned, no influence whatever. Starting, as the note does, with the coast line of California, in its lowest water, we shall find it at B, the intersection of HV and LW; before it (eastward) 240° of land, behind it (westward) 120° of water. When the point we are considering on the Californian coast is in lowest water, the apex of the tidal cone would be on the ideal world at H, where on our earth are the eastern coasts of Asia. Thus, there will be an expanse of open water all along the parallel from H to B. The differential attraction of the moon will therefore have its full force in producing a depression at B, and the water will be the lowest possible. As the point treated of rotates towards V, it passes into the region of high water, but as V is some 57° from the highest water at H′, the high water there (at V) will be but relative, and actually below mean level. Our point is at what the note states is improperly called "half-tide." As the point rotates further, it comes into the region of lowest water. But mark the difference! When last in lowest water it had continuous sea between it and the point under the moon. The water was then under the full squeeze of the pressure of gravity, or in popular language it was being drawn with the full attraction towards the moon. But now between it and the moon lies a region of solid land (America). There is no pressure towards the moon at the moment it is crossing the continuation of LW (back of the diagram). True there is a pressure towards V, but as I have already shown the high water at V is below mean level and therefore in the progress of our point on the Californian coast from V to low water there is but very little increase of pressure, and the water "falls slightly to a low water, which is sometimes merely indicated by a long stand!" The moon's influence alone permits a slight fall. When the sun has high declination, and his influence is added to the moon's, there may be no fall—only a long stand.

Thus we see that these abnormal tides of California are but an instance of strictest obedience to law. Every phase of the tidal movement, even the slightest variations of rise and fall, are just what might have been expected. Doubtless, if the earth were completely covered with water, there would be no such peculiar tides, but as this is not the case, the configuration of solid land causes complications of tidal movements, yet never takes them out of the kingdom of natural law.

Now, notice the remarkable contrast between the order of succession of high and low waters in the extract from the Admiralty Tide Tables quoted above, and the following note from the same publication, referring to the East Coast of Australia: "From April to October the night tides are higher than the day tides, and the reverse for the rest of the year. The usual sequence of the tides is from the lower low water to the higher high water." I have shown elsewhere the reason for the first half of this note, and that unless delayed by shallowing sea floors and abnormal retardation, day tides are always higher in the summer, and night tides in in winter. But the second sentence: On the West Coast of California the sequence is from lowest low water to lower high water, and on the East Coast of Australia from lower low water to higher high water. And the reason? When the East Coast of Australia is passing the point N in the diagram, it is in the region of lowest water, because there is a clear stretch of sea between it and the summit of the tidal cone at H′, and nothing to obstruct or interfere with the fall of the water. The locality then moves on to H′, into highest water, and then again to the region of low water at the back of N. But now the continent of Australia is behind it. There is no pull or pressure of the water to H′, because land is in the way, but only to the modified high water at V′. This low water will, therefore, not be so low as the previous low water. The succession will then be as stated in the Tables, and the difference in order of succession from that on the Californian Coast seen to be a necessity. It is quite impossible to explain either of these sequences by the dynamical theory, nor has any dynamical theorist ever given any explanation of them.

The diagram will also serve to illustrate the single day tides, which are simply cases of extreme diurnal inequality in the very place where, according to Laplace, it ought not to occur. The Tide Tables have the following note about the tides of British Columbia: "The diurnal inequality is great, causing apparently but one tide in the 24 hours on many days." Not a hint is given here, or in the dynamical text books, as to the cause, although it has been noticed by some observers and theorists that the phenomenon is coincident with high lunar declinations. By the dynamical theory these tides are simply "anomalous."

They cannot occur when the moon is over or near the equator, but when she has high declination, as in the diagram, it is quite obvious that with the cones where we place them there can be but one high and one low water in the lunar day, for a place situated on either of the parallels RW or LD. When the place is at W it will be in lowest water; in half a lunar day it will have rotated to R and have the highest water possible on that parallel, on the slope of the cone of which H is the summit. Twelve hours and twenty-five minutes later it will be back at W. These tides are a sheer necessity of our theory, and would be regular and well marked on the ideal world, and most noticeable and perfectly formed on the parallel of latitude, which is the same number of degrees from the pole, as the moon is from the equator. Being so far from the apex of the cone, the rise is small, and thus easily disguised, or interfered with by land configuration on our globe. They could be observed best on a small island south of the 60th parallel of south latitude, especially if the island had a long stretch of open ocean to the eastward of it. The conditions would then approximate to those on the ideal world.

CHAPTER IX.

TIDES OF FREMANTLE.

UNTIL quite recently, there have been no attempts to compute or publish locally any Tide Tables for the ports of Western Australia. When, however, Fremantle and the adjacent coasts were surveyed by Staff Commander Archdeacon, R.N., in 1873–4, the tidal observations taken were submitted to a searching analysis by the Hydrographic Office of the Admiralty, assisted by the ablest dynamical experts of the day. The results, according to one of the greatest living mathematicians, "disclosed very remarkable complications," and were admittedly inexplicable by the received theory of the world (Laplace's), which was the only criterion they were tested by.

Owing to its geographical position, the tides of Fremantle will be largely affected by retardation; and observation shows that wind and atmospheric pressure have a very marked influence on them. Subject to these interferences and that of the small derived wave from Cape Leeuwin, they will conform to the new equilibrium theory.

The moon's tidal influence is greatest in perigee when she is nearest the earth, and least in apogee the most distant point in her orbit.

SOLSTITIAL SPRINGS.

The maximum rise and fall, and greatest diurnal inequality, will take place at solstitial springs when the moon as well as the sun has highest southern declination coincident with perigee. This case is represented in Diagram XI., if we suppose the moon to be in the direction of M′, when for practical purposes we may assume the sun at new moon to be in the same direction, and to avoid complicating the figure that the parallel H′ V′ passes over Fremantle, which is actually only 3° south of it. Then the combined cone due to sun and moon will pass almost vertically over Fremantle in the day time, and give it the highest possible water there (at H′). As rotation carries the port behind the diagram past the circle of mean level, and then of lowest water to V′, there will be another high water (night tide), but it will be so small as to be actually below mean level. There will then be a slight fall to where the parallel crosses LW., followed by a long flood to highest water again at H′. This second low water will not be so low as the previous one, because the continent of Australia interferes with the free action of the moon.*

If the moon's declination is exactly equal to the sun's ($23\frac{1}{2}°$), the superimposed cones with maximum elevation would pass only 500 miles north of Fremantle, and give it nearly as high a tide as in the former case. The night tide at V′ would then coincide with the end of the dotted circle indicating mean level, and diurnal inequality, though still large, would be reduced. This dotted circle is about 55° or 3300 miles from the apex of the cone.

If the moon was full in the direction M, the water would not rise quite so high, nor fall quite so low as when the sun and moon were both over the Southern Hemisphere, and diurnal inequality would be less.

* The sequence here on the west coast will be similar to that on the Californian coast. (*See p.* 79.)

SOLSTITIAL NEAPS.

A week later the moon will be over the equator whilst the sun has moved less than 3° towards it, and their times of crossing the meridian will differ by about 6 hours. When the moon is over Q (in the direction E Q produced) and Fremantle near H′, she is doing her utmost under the circumstances to raise the level there, but the apex of the cone is 1900 miles north of the port, whilst the circle of mean level is only 1400 miles south of it. Consequently her tide more than half way down the slant side of the cone will be very much smaller than when she crossed the meridian within a few degrees of the port. At the same time, the sun six hours to the westward on the meridian through P and P′ perpendicular to the paper, and 20° south of the point over O, is trying to produce o w water at H′, and still further reduce the comparatively small high water caused by the moon. As rotation carries our port to V′, it will again find itself in high water under almost identically the same circumstances as 12 hours before. It will be practically the same distance from the anti-lunar cone as it was from the lunar cone at H′, and the sun will be relatively in very much the same position. The two principal lunar tides will thus be practically alike, and there will be no diurnal difference, except the small amount due to parallax. It is true that the sun will theoretically produce some inequality, but owing to his great distance it is so small that it may be neglected. The lower low water will be, however, when the moon is to the westward, exerting her influence over the open sea.

Thus, whilst there is at solstices a great difference between the range and diurnal inequality at springs and neaps, I will now show reason why a very different set of phenomena will be observed at the equinoxes.

EQUINOCTIAL SPRINGS.

At this season, if both luminaries are over the equator in the direction E Q produced, their joint cone will be a large one, especially if the moon be in perigee; but the apex is 32° from Fremantle, whilst the circle of mean level is but 23° further south. Consequently, the rise will be barely half what it is under the moon, and there will be no diurnal inequality, except that due to parallax, *i.e.*, to the cone on the opposite side of the earth being slightly smaller than that under the moon.

EQUINOCTIAL NEAPS.

A week later the moon will be near the latitude of Fremantle; in years of great declination within 3° or 180 miles. If in addition she happens to be in perigee, Fremantle will be very near the apex of a large lunar tidal cone, from which the sun, still near the equator, and six hours to the westward, will subtract something. As the solar tide is, however, so much smaller than the lunar, the rise may equal, or even exceed that at the spring tide a week before, especially if the moon was then (at the earlier period) approaching the earth.

As Fremantle rotates towards the circle of lowest water, the sun's influence, acting against the moon's, will keep the water from falling as low as it otherwise would, and it will rise again to high water at V′, which will be below mean level, and so there will be large diurnal inequality at equinoctial neaps. From V′ to the intersection of the parallel with L W., there will be a slight fall, opposed by the sun's action, and

interfered with by the Continent of Australia, lying between the apex of the lunar cone and Fremantle. This will be followed by a long flood to H′, which the sun's influence will detract from to a very moderate extent.

GENERAL.

The Solstitial tides I have described, are those pertaining to the southern summer, when day tides have the greater rise, and new moon produces the greatest diurnal inequality. At the winter solstice night tides will be the greatest, and full moon account of the largest diurnal difference, and this because the lunar cone is larger than the anti-lunar, whilst owing to the sun's great distance the solar cones are practically identical.

All the foregoing are the true equilibrium tides produced by differential pressure, with an allowance for the fact that the moon's influence is sometimes reduced by intervening land. The obstruction caused by the Australian Continent however produces a further modification, the amount of which is hardly predictable with our present knowledge. As successive elevations passing along the south coast raise the level immediately west of Cape Leeuwin relatively to that of the ocean north of this parallel where the land has obstructed the passage of the tidal wave, a derived tide must be set up. It is small in comparison with that up the Atlantic from the Cape, but of the same nature and must produce some effect however small on the times of H.W. and the amount of rise.

A strong north-west wind not only drives the surface water from the Indian Ocean on to the land, but also banks up the water from Cape Leeuwin, brought by the tide wave along the south coast. The low barometer accompanying the wind, indicating decreased surface pressure, helps to raise the level.

So much for theory, which I would not set much value upon, unless supported by observation. The Chief Harbour Master, Captain Irvine, informs me, that whilst in fine weather, with a steady barometer, the tides succeed each other with great regularity, a gale or series of gales upsets them altogether; and during the continuance of the bad weather neither heights nor times can be depended upon. When the weather settles down the tides resume the regular sequence which the new equilibrium theory predicts, and thus another set of anomalies can be expunged from the Tide Tables and Text Books.

CHAPTER X.

QUOTATIONS FROM MOXLY.

OSCILLATION.

"Is the tide an oscillation of water, as a wave or a current, across the world? To me the name 'oscillation' is a misnomer. On a world on which the tide had a free course, unimpeded by land or shallows, the tidal waves would follow one another over any spot at intervals of twelve hours. The tidal waves in such a case would be as old as the creation. There would be no new tidal wave ever formed. The wave would not move to and fro like a pendulum. This may seem a small matter, but it is these small matters that, originating in misconceptions, help to perpetuate misconceptions.

We must not, either, lose sight of the fact that when we speak of the tide wave as going round the world, it is really the world that rotates through the tide-wave, that is through the ellipsoidal form the waters of the ocean have taken.

We often hear from the philosophers that 'the ocean has not time to take the equilibrium form.' But it has had all the time from the creation of the world, and in fact has taken it from the beginning.

Were the world an ideal one, there would never be any distortion of the ellipsoid form. On our world this form is distorted by lands and shallows, but the distortions are periodic.

If the luminaries always occupied the same positions relatively to one another and to the earth, the tides would recur with unfailing regularity at any place on the earth's surface.

The configuration of the earth's surface remaining the same, the distortion of the ellipsoid would be the same exactly every day, and might be called permanent. As the luminaries are constantly changing their positions relatively to the earth and to one another, but in regularly recurring cycles of change, so the distortion of the tidal ellipsoid will also change in regularly recurring cycles.

But the word 'oscillation' as applied to the daily movement of the tide round the world, or to the daily rotation of the world through the tide is misleading. At the very least it is misleading, and can be seen to have misled even the experts, when applied to the tidal movements of the Southern Ocean. In that ocean no new tide is ever generated! The same form ever moves, and ever has moved, from east to west, the water composing the tidal protuberance changing from moment to moment, but the wave-form itself eternal, or at least æonian.

I admit that the so-called 'tides of long period'—that is, the fortnightly and half-yearly movements of the tide-cones north and south of the equator with the moon and sun—may be correctly termed oscillations, but it is not to these 'tides' the term is applied, but to the semi-diurnal results of the earth's rotation through the tidal spheroid. The 'oscillation' of which we hear so much is 'the semi-diurnal oscillation.' This oscilla-

tion is supposed to have a period of twelve hours, or, for the double movement, forwards and backwards, a period of twenty-four hours, and no such oscillation exists. The use of a term in an unreal sense—that is, when the term gives a false impression of what actually takes place in Nature—cannot but be mischievous, and in this case the mischief done can be easily discovered.

To conclude this discussion. There is in a true tide, running round the world, no oscillation, in the proper sense of the word—that is, no motion to and fro in opposite directions, east and then west alternately. The earth does not move to and fro in its diurnal rotation; the tide wave, where it is free to follow its luminary, does so as little, and it must be remembered that in these discussions of the astronomers, the world, the tides of which are considered, is an ideal world, or one on which the tide has free course. I believe it will be seen by my readers that mischief must ensue, and 'knowledge be darkened by words without wisdom,' when in the discussion of the tides on such a world the term 'oscillation' is introduced."

ROTATION AND RETARDATION.

"The polar axis of the earth is shorter than the equatorial diameter, because the earth is flatter at the poles than at the equator, and the equatorial diameter is still longer when it is measured as the diameter of the tidal spheroid. The shape of the earth is still more elongated by the tide. The earth at the equator is, when the moon is over it, flattened along a band and drawn out at two points. Tide is nothing but increase of curvature at some places and decrease of curvature at others, and this alteration of curvature is produced by pressure.

It will be seen that, considering tide as due to variation of pressure on the waters of the ocean, I have found that the tidal spheroid will have its longer axis lying in the direction of the luminary which, by interfering with the earth's gravity, is said to have raised the tide. Hitherto I have spoken as if the earth were at rest under the moon, but in Nature the earth is rotating. How will that rotation of the earth affect the position of the axis of the tidal spheroid? Were the earth an ideal world—that is, completely and uniformly covered with water—I should answer, rotation will have practically no effect. The ellipsoid formed once for all will be for ever preserved, and the earth will rotate through it. Were the water a perfect fluid and absolutely incompressible, I would not put even the slight saving clause, the word 'practically.' For, in an absolutely incompressible perfect fluid, pressure applied at one part must act instantaneously throughout the mass. The water, not being absolutely incompressible, though practically so, there will be a slight delay in the transmission of pressure, but it will be so small that it may be neglected.

But our world is not, in any sense, perhaps, an ideal world, and certainly it is not so in the sense in which the tidal theorist uses the word. Far from being completely covered with water, great tracts of dry land stretch across the world for thousands of miles. Where the world is covered by water, the depth is very unequal, and on the whole we must expect a very different series of phenomena from that which would occur on an ideal one. On an ideal world rotation would produce a very slight delay in the time of high and low water; the earth would rotate with its coating of water through the ellipsoid form of water.

Twice a day a given spot at the bottom of the uniformly deep sea would be covered by a depth of water greater than it would be covered by were there no tide; and twice a day it would be covered by a depth less than it would have been covered by were there no tide. I must be understood here not to be speaking of all places on the surface of the solid nucleus, for, as I shall show later, my theory asserts that there are places where there will be but one high water in the day, but for the present the statement made above may be allowed to pass. The time of high and low water would not be, as now, different at different places under the same meridian, for the formation of the tide-cones would be invariably regular. The state of things on our world is naturally widely different, for the tidal spheroid cannot but be seriously disturbed, not only by the masses of dry land, but also, though to a less degree, by alterations of the slope and level of the sea-floor.

The earth, with its coating of water, is rotating through the tidal ellipsoid. The floor of the ocean at a certain place begins to rise, and continues to rise till it appears above the surface of the water as a continent stretching perhaps for thousands of miles. From the point where the rise of the sea-floor begins, the water that, if the floor were level, would transmit the pressure upon it to the water next it, finds opposed to it, not water, but the (comparatively at least) unyielding surface of the solid nucleus of the earth. There can no longer be the equable transmission of pressure; there will be friction of the water against the rising sea-floor, and what we know as delay in the tide. A free wave travelling over the surface of a deep sea is not a current; the particles of water, at any moment, are not moving with a current motion, but up and down, and with a slight motion backwards and forwards, the total movement in both directions being almost zero. If an object be floating on the water, it will follow the movements of the water, and will not receive a sudden shock.

See how a well-trimmed, well-handled ship 'hove to' in a gale behaves. A huge billow towers a few yards away, many feet above her bows. A landsman on her deck shrinks back instinctively. To him it seems the wave must inevitably fall in a mass upon her! It passes under her instead, and one is scarcely conscious it has done so. There was no shock. Now in this case the wave could not, with exact propriety, be called a free wave, for it was exposed to the pressure of the wind behind it; but even so, the amount of actual motion forwards of the water composing it was so small there was scarce any perception of collision. When the object exposed to the wave is no longer free to move up and down or backwards and forwards, a widely different state of things ensues. Friction can turn such a billow into a mass of rushing water that will sweep well-nigh everything before it. But the rising sea-floor and the solid land lying across the course of the tidal wave cannot be torn from their moorings; they cannot rise with the rising water; and friction, which can turn the ocean wave we have seen passing harmlessly under the vessel into the 'breaker' that can destroy a pier and toss great masses of granite here and there, as if they were things of little weight—friction turns the tide wave into a moving mass of water. We have a tidal current and not a wave. This process is going on wherever the tidal wave is meeting fresh obstacles—that is, all the time that the sea-floor is rising against the tide, or the land is being carried by the earth's rotation into the region of elevated water.

Whenever, therefore, the floor of the sea rises against the pressure of tidal force, the high water will be delayed. Delay of the tide is a necessary consequence of the configuration of the land and of the slope of the sea-floor. As these vary at different places, so the delay of the tide will vary, and to say that because there is a delay of time of high water at any place, the equilibrium theory advocated in these pages fails, or is 'as far from the truth as it is possible for it to be,' is to say what is devoid of common sense. The equilibrium theory predicts such a delay as necessary. If an engine were contracted for, to be capable of drawing a train of certain stated weight, along a level, at a certain rate, and then the purchasers tested its power by setting it to draw the train up a steep incline, it would, I think, be held ridiculous for the purchasers to refuse to 'take over' the engine because it had not pulled the train up the incline at the rate at which the contractor had engaged it should pull it on the level.

So with my theory. It says that, on an ideal world, completely and uniformly covered with water, the tide will be under the 'tide-raising' body, but that where the conditions vary from the ideal, the time of the tide and the amplitude will vary also, and it is nothing less than ridiculous to say the theory has failed because the time and height of the tide vary for different places on the same meridian."

DERIVED TIDE AND TIDAL CURRENT.

"I have said that in the nature of things, high water should be under the moon, whereas it is the generally received doctrine that it should not be in that position, but 90° behind it. But mark, I have not said that in such a world as ours, the most noticeable tide will be in all cases under the moon. What I do say of such a world as ours, is that wherever there is a possibility for the tidal-wave form to have an unimpeded course round the earth at any parallel, then the tide will be under the moon. And further, should this possibility exist, and the other oceans be comparatively narrow (the narrow oceans opening into the tidal belt) the noticeable tide in these oceans will be derived from the tidal belt, and this derived tide will proceed along these oceans with a speed depending on the depth of water, and a height depending very much upon the breadth of the space over which the tidal wave in its progress has to spread, and the configuration of the shores and the slope of the sea floor at and near the place where the tide is measured. The main tide of the seas and narrow oceans will, in fact, be a derived tide—that is, a tide derived from the belt across which what I shall call the true tide is passing.

Where then, on the surface of the earth shall we find a sea in which it is possible for a tide to follow the moon in her passage from east to west around the globe? On looking at the map of the globe we find that nowhere does such a sea exist except in one region—that of the great Southern Ocean. Here and here only there is a stretch of water round the earth."

After showing, as I have already done, that the tide in this ocean is under the moon at the few stations where it has been observed and up to the 45th parallel in the South Indian Ocean, Moxly continues :—

"The theory of the astronomers as to the diurnal tides fails absolutely where it should have stood the test best. It is not too much to say that the current theories fail generally to agree with facts; so much so that Sir George Airy was driven to confess that 'we cannot at all account for

the position of the co-tidal lines of the ocean tides.' Now here I have no need for a hypothetical refuge; for the tide, where it has a chance, is as regular as the sun and moon themselves, and equally with them just where it ought to be. I am fain to point out the contrast of results so far obtained from my 'scheme,' with the results obtained from the former theories. So far as I have gone—it is not far, but so far as I have gone—the agreement between theory and fact is perfect.

To proceed to the next step. How, on my principles, are the co-tidal lines and the phenomena of the tides generally in the Atlantic Ocean to be explained? There is really no difficulty. The tide is in its due place at the due time. The true tide *under the moon*, save when the actual time of highest water—a different thing, as I hope to show—is delayed by shallowing seas, where all tides will necessarily 'drag,' according to my view, and also according to the accepted theories, and where the tidal wave, also necessarily, becomes a tidal current; the derived tide—in the case of the Atlantic the principal tide—following its course as a free wave, its velocity depending upon the depth of the sea it traverses. For the Atlantic this velocity is found to be, at all events as far as Cape Clear, some 520 miles an hour, or roughly what a sea of a depth of 3½ miles would have it.

This statement may meet with some opposition, but let us put a case. Suppose a narrow sea, its length lying north and south and opening into the Southern Ocean. Let us give this sea a breadth of fifty miles. It is then a long canal, and will have no appreciable tide (east and west) of its own. It will have a tide, a true tide of its own, following the moon from east to west, just as a sea like the Caspian will have a tide of its own, but quite inappreciable. But the sea is supposed to communicate with the great tide-bearing Southern Ocean. The high water of this ocean will therefore pass the entrance of the narrow sea twice in the lunar day. What consequence will inevitably ensue? Will not the elevated ocean as it passes the sea of lower level flow down into it? Will it not flow down, not only as a wave, but as a current, pushing the water of the narrow sea before it as a wave and raising the level of the water in the sea? Will not the wave thus raised flow right up the narrow sea, unless and until inequalities of depth and the jutting promontories of its coasts dissipate the wave by friction? Remember, this we are speaking of is a free wave. We are dealing now with facts of a different order from those that meet us when we are treating of the forced wave of the true tide. The water from the Southern Ocean will not, of course, enter the narrow sea only at the moment of high water, it will begin to flow into it as soon as it rises above its level. Well, will not this derived wave require time to travel along our narrow sea? Should our sea broaden at any part, will not the wave spreading over a larger surface decrease in height to gain in height again wherever the sea is hemmed in?

Given that this wave's velocity is five hundred miles an hour, will it not be four hours after high water at the point whence it was derived, before the high water of the derived tide reaches a port or island situated two thousand miles up the sea, and away from the ocean? Suppose your island three thousand miles away up the narrow sea, will not the moon have travelled nearly a fourth part of its way westwards round the world before the island is washed by high water? And will it be any proof of irregularity in the true tide, or of its being behind the moon if there is

low water at the island when the moon is passing its meridian and high water there at the moment when it is in quadrature ? Surely not ! And there is no difficulty to be explained. It will not be correct to speak of the moon as 'having travelled 90° to the west before she succeeded in *dragging*' up the tide of the island. It will be incorrect to speak so, not only because the moon is quite incapable of dragging a single drop of water after her, let alone a mighty tide, but it will be incorrect because at the moment of high water at the island, the little influence the moon is exercising upon the narrow sea is exercised in giving an opportunity to gravity to make it low water there and not high water.

Now let us give our sea a breadth, not of fifty miles merely, but of from four thousand miles to, say, five thousand miles, and we shall have approximately our Atlantic Ocean, and in it there will be, in addition to the derived tide running north and south, a 'true tide' of its own. This true tide will be under the moon, but where the water is heaped up by running against a coast-line, and all the more should the coastline be concave, the highest water will be behind the moon.

As the point of observation is chosen remote from the origin of the derived wave or near it, so the true tide will precede the derived tide by a greater or less interval, until if you take your point far enough north the true tide will precede the derived one by twelve hours, *i.e.*, it will coincide with the derived tide which started on its way twelve hours before. Where this is the case the combination of the two tides will produce an extraordinary height of tide ; I mean a tide higher than the ordinary or average tide of the sea. If, owing to the configuration of the coasts the derived-tide wave should be running north-west or west instead of north, the waves will perhaps add to each other's impulse ; certainly they will do so where in shallowing waters the waves become currents. The mass of moving water will be increased.

Now let us see if there is any place on the coasts of the Atlantic where this *must* happen. Above latitude 5° N., *i.e.*, above the comparatively narrow passage between Cape San Roque and Sierra Leone, the Atlantic spreads out rapidly to the west. The derived tide will therefore take a more westerly direction, and by the time it reaches the North American coast, about the 45th parallel, it will be running chiefly west, or perhaps north-west, and so right against the shore of the sea there, and not along it. This tide will therefore be piled up. Now, if you look at the co-tidal chart of Sir George Airy, you will see that the tide which left the Southern Ocean at time of full moon does not arrive at highest water along the coast of New Hampshire and Maine till more than seventeen hours afterwards, and so the time when the full-moon derived tide has reached the entrance to the Bay of Fundy will be the same as that of the arrival of the true tide under the moon of the following day. The two tides thus coincide, and as they are, on the coast of Maine, running in the same direction, we might reasonably expect a tide of extraordinary height. When we call to mind that, at the time of greatest declination of the moon, north or south, the tide of the Southern Ocean, at the latitude whence the derived tide takes its origin, will be largest, and the true tide under the moon along the parallel of 45° N. lat. will be near its greatest, it will be seen that near that parallel (45° N. lat.) the greatest possible tides may be expected. It is just at this latitude the entrance to the Bay of Fundy lies and the combined currents—the tidal waves near the shore tend to

become currents—flow in. This great combined tide striking against the coast of Maine is reflected back against the Nova-Scotian coast and, as it were, trapped in the Bay of Fundy. There is no escape for it, and the level of the water in the bay rises to an unusual height. We have, in fact, and ought to have, the greatest tide in the world. Now, former explanations of the 'extraordinary' tides of the Bay of Fundy seem to be quite inadequate. These explanations are something as follows. 'The shores of the bay converge rapidly, narrowing from a wide mouth to little more than a point, and, as in the similar case of the Bristol Channel, the tide necessarily attains a great elevation. The converging sides of the bay pen the water into narrower and narrower limits, and so it becomes heaped up at its upper extremity.' Well, one has but to look at a map to see that there is no similarity between the configuration of the bay and that of the Bristol Channel. It is not too much to say there is no convergence of the shores in the Bay of Fundy. Towards the upper extremity Cape Chignecto divides the bay into two shallow creeks; but in one of these, and that the one in which the rise of the tide is greater (the Bay of Mines), the water, after passing through a narrow entrance, expands over a wide surface. The hemmed-in tide in both bays is very high, but the point of the Bay of Fundy at which the tides rise highest is not at either of these extremities, but at Annapolis near the entrance, and on the Nova-Scotian coast, where the reflected waters from the coast of Maine impinge, and where tides of more than a hundred feet have been measured.

There are extraordinary tides in the bay because there are extraordinary opportunities. Nowhere else in the world do two such tides combine; nowhere else is such a trap prepared for them!

It will be readily understood that the most marked effect of the true tide upon the derived, in such a sea as the North Atlantic, will be produced when the tides synchronize at any place. Then the elevation at high water (other things being equal) will be greater, and the depression at low water greater than at places where the true tide can but mask in some degree the rise and fall of the more conspicuous derived tide. The Mediterranean Sea offers another noticeable coincidence of fact with what my theory gives as its result. It was till recently supposed that the tides in the Mediterranean were almost inappreciable, and it was considered impossible that there could be anything but a very small tide there. If you will remember, the theory adopted by me is—that every sea on the surface of the earth will have its own true tide; that where the sea is narrow, from east to west, this tide will be inappreciable, but the wider the sea, the more noticeable the tide. Further, that on a coast running north and south across the course of the tide, the water will be swept back, and the tide retarded and raised. Now, between the Syrian coast and the Gulf of Cabes, the Mediterranean covers a space of 25°. At Cabes the coast-line runs north and south, and along this coast a spring tide of some six feet has been measured (*Tide Tables for 1898*, p. 179).

It is abundantly clear that such a tide could not possibly be raised in the Mediterranean by any inflow through the narrow passage of the Strait of Gibraltar. And if we could bring ourselves to believe in such an impossibility, it would pass the wit of man to account for the fact that it is not near Gibraltar, but many hundreds of miles away, and round a corner, so to speak, on an east coast that this tide is found. Surely here there is

but one view possible. The tide is the true tide of the sea, piled up upon a coast running right across its track—a tide derived from this running up the Adriatic, and arriving at the extremity of that shallow gulf some nine or ten hours after the moon.

The Mediterranean and the Adriatic teach the same lesson, on a small scale, that the Southern Ocean and the Atlantic do on a large one."

SINGLE TIDE PARALLELS.

"The tide under the luminary, that is, on its meridian, will be, except when the body is over the equator, higher than the tide on the opposite side of the earth along the parallel of the place where the tide is measured; and the difference in elevation of the tide at a place situated in certain latitudes will be so great that it may, and sometimes must occur, that there will be but one tide in the lunar day—a high water, that is, on the meridian of the moon and low water opposite to the moon. This seems a surprising result, since we have been accustomed to think that if there is a tide at any place there should, or, rather must, be a tide at the opposite side of the earth. The apparent contradiction is due to the loose use of the term 'opposite.' At one time we use the word to express the position of a place opposite through the centre of the earth, and that is the correct use of the term; but, again, we use the word 'opposite' to signify the position of a place 180° away from another along the same parallel of latitude. Now, although there will always be tides under the moon and opposite the moon through the centre of the earth, whose difference of elevation will be but that due to difference of parallax at the two places, it is quite different as to tides on the upper meridian of the moon and on the lower meridian at the same latitude.

Referring to Diagram I., with the moon in direction H M, the highest water will be at the two points H and H′ and L W will represent half the circle of lowest water. If the moon's declination be 29°, R and D will each be 32° from the points of highest water, whilst L and W are in absolutely lowest water. Now, let the earth be supposed to turn on P P′ from E towards Q, the place at R in the diagram will have reached the position at first occupied by W in some 12½ hours, thus passing from highest water on that parallel in 12½ and not 6¼ hours. During the next 12½* hours the place will have got back to high water, and will thus have had absolutely but one high and one low water in the lunar day. It is evident that no place situated on either of the parallels R W or L D can have more than one true tide in the lunar day when the moon's declination is greatest either north or south. Places near these parallels will have practically but a single daily tide. Now, if we look at an atlas or a terrestrial globe, we see at a glance the quite satisfactory explanation of the "most remarkable tides" of Sitka Island and Petropaulofsk. Sitka Island lies in north latitude 57°, and is therefore very close to the line R W; Petropaulofsk is in north latitude 54°, and therefore for both places there can be high water but once in the lunar day.

At first sight one would be disposed to say: 'If these places have high water when on the meridian of the moon, they must also have high water when 180° away, for that is opposite the moon!' The diagram, however, shows where the fallacy lies, and the tides of Petropaulofsk cease to be 'most remarkable' and 'abnormal.' They are seen to be necessary and normal. Now, here was a peculiarity of the tides of the Pacific—a

* Twelve lunar hours=12 hrs. 25 min. solar time.—J. F. R.

peculiarity which remains to this day inexplicable, if it be supposed that the true tide is not under the moon; whereas, once it is understood that the greatest elevation is under the moon, the tides are seen to be not merely possible but necessary. One might think, perhaps, at first sight, that it would not make any difference in the behaviour of the tide at Petropaulofsk whether the greatest elevation of the surface of the ocean of an ideal world were under the moon or 90° east or west of her, as Petropaulofsk must in each rotation be at one time on the moon's meridian and at another opposite to her. It will be seen, however, that the possibility of such tides as those at Petropaulofsk depends absolutely upon the position of the tide with regard to the moon, and that a single tide in the lunar day cannot ever occur at any place unless the greatest elevation of the water be directly under the moon. Suppose, for instance, that the highest water is at points 90° on either side of the moon, and see what curious results will follow.

The summits of the two tidal-cones must then be on the equator, and lowest water under the moon and opposite her whatever her declination may be. Let the moon move north and south—were the declination even 90° and the moon standing over the North Pole, the highest water 90° away must be at some point on the equator, and the circle of depression will pass under the moon. Suppose, again, that the moon is fixed for a day at greatest declination as we know it, say, 29° (the moon is practically fixed for a day at greatest declination), the highest water is then at two points on the equator 180° apart, and only places on the equator can rotate through these points, *i.e.*, have highest tide. The tide will dwindle from the equator towards each pole and at 54° 44′ N. and S. will vanish, a depression existing from the vanishing point of the elevation to each pole. Petropaulofsk will rotate all the day through water at mean level, or lower than mean level; for that place there will be no positive elevation of water, and it will pass through greatest depression not once but twice in the day. A single tide in the day will be an impossibility! This, I believe, is incontrovertible.

But Petropaulofsk has practically a single tide in each month, when the declination of the moon is great, and Sitka Island still nearer the line R W, has almost absolutely a single tide. Now, here, as I said, is a fact of observation inexplicable on any other hypothesis than that the apex of the tidal spheroid is under the moon. On my principle it becomes not only explicable, but more, it is seen to be necessary.

A striking part of this discovery of mine is, that I was not thinking at all of Petropaulofsk when I worked it out. I was looking merely for the general results of my theory, and when I found it led to the conclusion that at places near the parallel of 60° N. and S. there would be at certain times but one tide in the day, I almost gave up the inquiry in disgust. I had never heard that places existed where there was but one tide in the day; but when I read that Whewell had found such places, and that they were just where I wanted them, whereas to Sir George Airy they were a standing puzzle, I could scarcely avoid looking upon them as strongly, though on my part quite unexpectedly, confirming the view I had on totally different grounds taken. It is here, as in so many other instances I have given; the theory was not set up to account for the facts, which were indeed unknown to me, but the facts, as I discover them, fall into their due place and no additional hypothesis is required.

One thing at least seems clear; on my view we must cease to speak of the tides of Petropaulofsk and Sitka as 'peculiar' or 'abnormal,' for they are only 'remarkable' in the same sense as an eclipse is a peculiar or remarkable event. While men remained in ignorance of the cause of an eclipse, no doubt that phenomenon was considered 'most remarkable.' Now we have ceased to speak of such an occurrence in that way. Thus also we shall cease to speak of these tides as peculiar, remarkable or abnormal, when we have learnt their cause and recognized that they are the regular and orderly effects of constant universal law.

A specious objection may be raised to the above reasoning. It may be said: 'We know as a fact the tide at Petropaulofsk is not under the moon, and therefore your whole argument is demolished by the hard logic of facts!' The tide at Petropaulofsk is not under the moon and could not be, for the tidal spheroid on our world is necessarily distorted by the land. But the distortion is periodic, and I may say for any place permanent. The time when the tide occurs will be delayed, and the tide swept back from under the moon, but each tide is that which if the land had not interfered with it, would have been under the moon some hours before.

When the moon's declination is 20°, the parallel at which the diurnal inequality causes one tide in the day is the 70th, and when the declination is but 10° the parallel of the single day tide is the 80th, and so on.

What would be remarkable, and indeed impossible upon an ideal world, would be to find a place much farther from the Pole than those we have been considering with a single day tide. A single tide in the day near the equator, or even at the 45th parallel, might plausibly be called 'remarkable.' On our world such a tide would only be possible through the effect of friction of the rising sea-floor dissipating the smaller of two semi-diurnal tides. The friction that a great tide would overcome might prove too much for a small tide still further diminished by diurnal inequality: it might fail to make its way."

GEOMETRICAL DEMONSTRATION OF ACTION OF TIDE-GENERATING FORCES.

"If the earth were a sphere completely covered with water, it would, under the combined influences of the attractions of the earth and moon, assume an ellipsoidal form. There would be a wide band of depressed water stretching all round the earth for about $70\frac{1}{2}°$, and on each side of this depressed band, a cone cap with the apex of each cone opposite that of the other, through the centre of the earth, and both apices in the line passing through the centres of the earth and moon.

In all this, my theoretical view is the same as that of the original theory, and I am not, of course, called upon to defend what we are all agreed upon; but as this book is intended for the perusal of people who are not always familiar with the reasons for the existence of tide—and I find that very many are still puzzled by the existence of tide on the side of the earth remote from the moon, and that there are also many who find a difficulty in seeing how the attraction of the luminaries can increase the power of the earth's gravity at one place and counteract, and so lessen, the earth's gravity at another—I am going to devote some space to as clear an explanation of these things as I can give. I have, however, no wish to weary my readers who may not be interested in the exact mathematical demonstration of the reasons why things are as they are, and this part of the book

may be passed over by any one who does not care to give it some attention. At the same time, I think I may promise any reader who peruses the following pages that he will never again be puzzled by the existence of tides on the side of the earth remote from the moon, or by the assertion that the tidal force of the luminaries is, at one part of the earth's surface, employed in assisting the gravity of the earth to make things heavier, while at another part of the world it is counteracting gravity and making things lighter than they would be were there no luminaries.

But there is one argument to which the attention of readers who are anxious to save themselves trouble may be called. It is probably the fact that no one feels much difficulty in agreeing with the statement that if the moon is counteracting gravity most immediately under her, a tide will naturally rise at the point immediately under her. It is the undoubted existence of the tide on the opposite side of the world that seems paradoxical! Now, nothing can be clearer than that if two bodies are being drawn together by any force, or set of forces, the bodies will eventually approach and come together unless these forces are counteracted by an opposite force. The moon and earth are being drawn together by the attraction of gravity, yet they do not come together. There must, therefore, be a force equivalent to the force of attraction, but acting in an exactly opposite direction, which keeps the earth and moon asunder. It does not matter what we call it! 'Centrifugal force' will do for a name for it, if you like. The point for us is that the force does exist—must exist, and that it is exactly equal to the attractive force, but opposite in direction. Well, then, if the attractive force raises a tide under the moon, the force opposite the attractive force will produce a similar effect on the opposite side of the world. I think it will be evident that if we have to admit the existence of a force, exactly the counterpart of the attractive force of gravity, but acting in the opposite direction, we must also be able to imagine the effect of that force producing the same results, on its side, that attraction does on the side on which the attraction is evidently acting. Whatever effect the one force or set of forces will produce, the other set will produce a similar effect, but, of course, in the opposite direction. Some of my readers may perhaps have their difficulties cleared away by this simple reasoning; for those who wish to go more fully into the matter, and see exactly how and why things are as they are, I have pleasure in offering the following almost equally simple demonstration.

Let us suppose, then, that E, in the accompanying figure, represents the centre of the earth—which, remember, is for tidal calculations treated as a sphere—and M that of the moon. C will be the point of the earth's surface where the moon will be exactly in the zenith, and Q the point where the moon is in the nadir. A B is the line drawn around the earth 90° away from the moon, and from any point on this line the moon will be on the horizon. It will be understood, however, that as regards the distance of M from E, the figure makes no pretence of being even an approximation to the true proportion. The figure to be correct as to this, should give the line M E equal to sixty times E C, or the earth's radius; that is, M C should be equal to fifty-nine times E C, and M Q should equal sixty-one times E C.

The problem is, to find what the tide-raising force is at any point, say P, on the earth's surface. The 'tidal force' at any point, is not,

of course, the total of the moon's attraction at the point, but the difference between her attraction at the point and her attraction at E, or between her attraction at the given point and her average attraction. To find the tidal force at P, we must have something that may represent for us the total attraction of the moon on P. It will be most convenient if we take the line M P as representing this —the attraction of the moon on P—both in magnitude and direction. It is evident that the line taken to represent the attraction of the moon at E, or the average attraction, must be less than M P, and less in proportion as the square of the distance of the moon from E is greater than the square of the distance of the moon from P, for gravity varies *inversely* as the square of the distance. If, then, we take a point X in M E, so that M X : M P : : M P^2 : M E^2, M X will represent in magnitude and direction the attraction of the moon at E—that is, remember, on the supposition that the line M P represents the attraction of the moon at P. Now, as the earth does not approach any nearer to the moon for all its attraction, we may take it that, in effect, it is kept from doing so by a force equal to the attraction of the moon upon the earth, but acting in exactly the opposite direction to that in which the attraction of the moon acts. This force it used to be the fashion to call the 'centrifugal force' of the earth in its monthly orbit round the common centre of gravity; and though I do not like the term, and regard it as in several ways mischievous, it is so familiar and is used so often still, that I let it pass. What we are concerned with is the fact that the earth is kept from being drawn nearer to the moon, and the force that has this effect may be taken as equal to the attractive force, but opposite in direction.

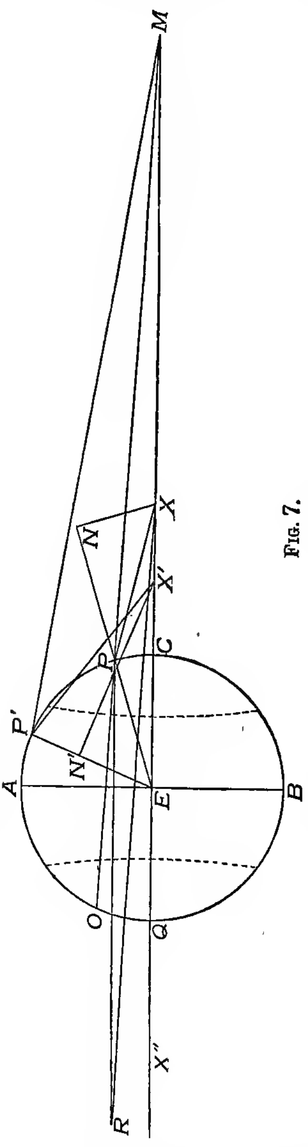


FIG. 7.

The average force acting oppositely to the moon's attraction is obviously equal to the average attraction, and may therefore be also represented, on our scale, by the line M X. If, then, we draw from the point P a line P R, equal and parallel to M X, in the opposite direction, this line will represent the average force that keeps the earth from falling into the moon.

Completing the parallelogram P R X M, and drawing the diagonal P X, this line, P X, will represent the resultant of the two nearly opposite forces acting on P, and will represent, therefore, what is called the 'tidal force' at P both in magnitude and direction. As the direction of P X is neither perpendicular nor tangential to the surface of the earth at P, it can be resolved into two forces, one of which will be perpendicular to the line E P, while the other will be in the line E P. Drawing then from X the line X N, perpendicular to E P produced, the lines P N, N X will represent the components of the force given us by P X. The force P N

is plainly acting vertically at P, while N X is parallel to the tangent at P, and therefore represents the tangential force, while P N is said to represent the vertical or normal force. If P be taken farther away from C, at a point 54° 44′ from C, it will be found that the new P X will be itself a tangent at the new P; the vertical component P N no longer exists, for the tangent (the new P X) cannot be resolved into two forces, and so the normal, or vertical, component of the tidal force is said to vanish at the new P. If, however, we take another point farther still from C, the normal, or vertical, component is seen again; but now it does not lie away from the centre of the earth, as regards the point at which we are considering the tidal force, but towards the centre of the earth. Let P′ be the point, and take P′M as representing the attractive force of the moon at P′. P′M is more nearly equal to M E than P M was, and the point X must be moved, to X′ say, if M X′ is to be in the same ratio to M P′ that MP'^2 is to ME^2.

Following the same line of reasoning as in the former case, we find P′X′ as the representation of the tidal force at P′. When this is resolved into rectangular components by drawing X′N′ perpendicular to E P′, we have, as representing the tangential or horizontal force, N′X′, and as the normal or vertical force, P′N′. But this line (P′N′) lies from P′ towards the centre of the earth, and not, as in the former case, away from the centre of the earth. This indicates that the vertical part of the tidal force at P′ goes to assist gravity, or to produce a pressure on the surface water of the sea at P′ vertically towards the centre of the earth. As the distances M A and M E are practically equal, to find the tidal force at A, X must move up to E if M X is to be to M E as $ME^2 : MA^2$, for ME^2 and MA^2 are equal. In that case, A E becomes the normal, or vertical, force, and the tangential force in its turn disappears. Thus the tidal force at A, or 90° away from C, is altogether a depressing force. As P is moved towards C, we find, on the other hand, the line N X, representing the tangential force, diminishes till, when P has reached C, the perpendicular N X on E P vanishes, for E P is then in the line E M. Thus we see that at A tidal force is completely vertical, but increasing the pressure of gravity, and so producing a depression of the surface of the sea at A; at a point between A and C the tidal force is tangential only, and the pressure on the water is that due to gravity unassisted by any other force, while at C the pressure of gravity is counteracted, and counteracted more than at any other place. Readers who have even a slight knowledge of mathematics will see easily why the decrease of the pressure due to the influence of the moon is twice as great at C as the increase of pressure was at A, and also why the point at which the vertical force vanishes is that 54° 44′ from the moon; but as the proof would be of no service to those without any knowledge of trigonometry, and unnecessary to those who have such knowledge, it would be useless to give it in the present work. As the pressure of gravity on the surface of the sea is increased at A and diminished at C, and as water answers readily to pressure, the true cause of tide will, I hope, be apparent to any one who is not blinded by prejudice, or who does not pin his faith on some teacher of repute, and get rid of the necessity of thinking for himself. But I have not yet said a word as to the tide on the side of the earth remote from the moon. My readers are now in a position to 'take in' the reason of the anti-lunar tide at a glance. Let us consider the tidal force at the point O in the figure. If we take O M

as representing the attraction of the moon at O, it is evident that the line representing the attraction at E must be greater than O M, for the attraction at E is greater than that at O, since E is nearer to the moon than O is.

Our new point, X″, must be taken in M E produced, if M X″ is to be to M O as $M\,O^2$ is to $M\,E^2$, for $M\,O^2$, or the square of the distance of O from the moon, is greater than $M\,E^2$ or the square of the distance of E from the moon.

By following the same method as in the other cases, that is, applying to O a force equal and parallel to M X″, but opposite in direction, completing the parallelogram of forces, and drawing the diagonal O X″, we find O X″ representing the tidal force at O in magnitude and direction, and this direction is, of course, such as will give eventually the greatest decrease of pressure of gravity for the hemisphere A Q B at the point Q, as in the hemisphere A C B the maximum counteraction of gravity was at C.

Thus we arrive at the conclusion that on an ideal world there will be a great band of depression of surface below the level the water would take were the luminaries non-existent, the band of depression being more than $70\frac{1}{2}°$ of the earth's surface in breadth, and two regions in which the water would be higher than the level of water were the luminaries non-existent. The dotted lines in the figure may be taken to represent the circles at which vertical force vanishes. The pressure along these lines is that due to the earth's gravity alone, and along them the water will keep to the level it would have in the absence of the luminaries. Over the space lying between the dotted lines is a band of depressed water, running, as you see, quite round the world.

Between the dotted lines and the points C and Q are the regions in which the water is elevated above the original, or what I shall call the 'mean level.' It is easy to see that, as the region of depression is so large in comparison with the total area over which there is elevation, the lowest depression will not be so much below mean level as the greatest elevation is above mean level. In fact, the depression below mean level along the line of lowest water will be but half as much as the height of the greatest elevation, but the line of lowest water is a complete circle round the earth, while the elevation culminates in but two points. The elevated regions are but caps of cones. I cannot show this without more mathematics than my readers would care for ; but the fact I wish to draw attention to is, roughly, evident enough."

TIDAL DATA FROM VARIOUS AUTHORITIES.

Sun—	
Distance in millions of miles—	
Greatest	94·6
Least	91·1
Mean	92·7
Diameter—	
In miles	865,000
In terms of earth's	109
Mass—	
In terms of earth's	330,000
Density, water being equal 1	1·4
Moon—	
Distance in miles—	
Greatest	221,000
Least	260,000
Mean	239,000
Diameter—	
In miles	2,160
In terms of earth's	·273
Mass—	
In terms of earth's	$\frac{1}{81.44}$
Density, water being equal 1	3·5
Earth—	
Diameter in miles (equatorial)	7,926
Mass—	
In terms of earth's	1
Density, water being equal 1	5·66

The moon rarely approaches either of the above limits. The usual oscillation is 13,000 each side of the mean distance. Her volume equals $\frac{1}{50}$ that of the earth.

SUN'S ATTRACTION COMPARED WITH THE MOON'S.

Being directly as the mass and inversely as the square of the distance.

$$\left.\begin{array}{l} \text{As } 390^2 : 1 \\ \text{and as } 1 : 81{\cdot}44 \times 330{,}000 \end{array}\right\} :: 1{,}521 : 268{,}752 \text{ and } :: 1 : 177.$$

SUN'S TIDAL FORCE COMPARED WITH THE MOON'S.

As $390^3 : 81{\cdot}44 \times 330{,}000 :: 1 : {\cdot}45$.

Roughly as 60 (millions) : 27 (millions) :: 1 : $\frac{45}{100}$.

The sun's attraction is thus 177 times greater than the moon's, whilst her tide-raising force is more than twice as great as that of the sun.

SOLAR AND ANTI-SOLAR TIDES COMPARED.

As $92{,}704{,}000^3 : 92{,}696{,}000^3 :: 100 : 99{\cdot}97$, so that even with a tide of 30 inches the difference would be less than $\frac{1}{100}$th of an inch.

RELATIVE HEIGHTS OF LUNAR AND ANTI-LUNAR TIDES.

As $(\frac{1}{59})^3 : (\frac{1}{61})^3$ :: 42 in. : 38 in. and :: 100 : 90·5.

RELATIVE HEIGHTS OF LUNAR CONES ABOVE MEAN LEVEL AT PERIGEE AND APOGEE.

With extreme ellipticity—
As $256{,}000^3 : 217{,}000^3 :: 42$ in. : 25·58 and :: 100 : 60·91.

With usual ellipticity—
As $248{,}000^3 : 222{,}000^3 :: 42 : 30{\cdot}13$ and :: 100 : 71·73.

The moon revolves in 27·322 days, completing the circle of 360°.

In which time the earth advances in its orbit $\frac{27{\cdot}322}{365{\cdot}242} \times 360° = 26{\cdot}93°$.

The difference between the daily orbital speeds of moon and earth is—

$$\frac{360 - 26\ 93}{27{\cdot}322} = \frac{333{\cdot}07}{27{\cdot}322}$$

To overtake the earth in orbit and complete lunation requires—

$$\frac{26{\cdot}93 \times 27{\cdot}322}{333{\cdot}07} = 2{\cdot}209 \text{ days.}$$

In which time the moon will have described an arc of 29·1°.

The metonic cycle of 19 solar years = 235 lunar months.

SPEED OF FREE WAVES IN THE OPEN SEA.

Depths. English Miles.	*Speeds.* English Miles.	Knots.
1	281	244
2	398	345
3	487	423
4	562	488
5	629	546
12·75	1,003	872
13 75	1,038	902

The two latter are the speeds at which, owing to rotation, the forced wave of the lunar and solar tides travel round the world at the equator.

ST. JOHN, N.B.

DATE.	☽'s MER. PASS. STANDARD TIME.	DEC.	PHASE.	TIMES OF H.W.	HEIGHTS IN FEET.		—
					H.W.	L.W.	
June 7th	0.27 p.m.	24° N.	New, 1.16 p.m., 7th (5th Perigee).	11.22 a.m., 11.48 p.m.	26.1 & 28.1	0.2 & 1.9	Lat. and Dec. same name; $11\frac{1}{2}$ hours after superior transit.
June 23rd	0.43 a.m.	$26\frac{1}{2}$° S.	Full, 8.12 p.m., 22nd (17th Apogee).	11.36 a.m., 11.51 p.m. ...... 0.12 p.m. ...... 0.29 a.m., 0.50 p.m.	22.5 & 24.2 22.5 24.4 & 22.6	3.8 & 5.5	Lat. and Dec. contrary names; highest tide $11\frac{1}{2}$ hours after inferior transit.
July 6th	0.15 p.m.	$26\frac{1}{2}$° N.	New, 9.20 p.m., 6th (3rd Perigee).	11.9 a.m., 11.29 p.m.	24.9 & 27.0	1.2 & 2.9	Lat. and Dec. same name; $11\frac{1}{4}$ hours after upper transit.
December 15th December 17th	11.57 p.m. 1.03 a.m.	26° N.	Full 10.05 a.m., 16th (15th Perigee).	16th, 11.19 a.m., 11.48 p.m.	27.8 & 26.0	1.7 & —0.1	Lat. and Dec. same name; highest tide $11\frac{1}{3}$ hours after superior transit.
December 30th December 31st	11.36 a.m. 0.28 p.m.	27° S.	New, 4.21 p.m., 31st	30th, 11.06 a.m., 11.30 p.m. 11.45 a.m.	23.6 & 22.1 23.8	5.7 & 4.3	Lat. and Dec. contrary names; highest H.W. $11\frac{1}{2}$ hours after inferior transit.

The mean of the above five solstitial spring tides gives the highest H.W. 11.4 hours after the superior transit of the moon when she has N. Dec. and after the inferior transit with S. Declination, agreeing in a way with the rule for the ideal world; but this is only 0.6 before the transit that would reverse the rule, as Whewell found was the case for North-Western Europe. For these tides diurnal inequality is more uniform than at Halifax, and only about half of the greatest difference between springs and neaps, which in some cases it equals. It is greater at springs than at neaps, and at H.W. than at L.W. The difference between diurnal inequality at H.W. and at L.W. is more marked at neaps than at springs.

The time of meridian passage is that for Greenwich, corrected for longitude, and the standard time of 60° W., for which the tables are calculated.

HALIFAX, N.S.

Date.	☽'s Mer. Pass. Standard Time.	Dec.	Phase.	Times of H.W.	Heights in Feet. H.W.	Heights in Feet. L.W.	—
January 11th ..	0.33 p.m.	25° S.	New, 11.51 a.m. (17th Perigee).	7.56 a.m., 8.35 p.m.	6.1 & 5.6	2.1 & 0.8	Lat. and Dec. contrary names; highest tide follows lower transit agreeing with rule for ideal world.
January 26th ..	1.06 a.m.	22° N.	Full, 11.51 a.m., 25th.	3.32 a.m., 9.18 p.m.	6.2 & 5.9	1.7 & 0.6	Lat. and Dec. same name; highest tide follows upper transit according to rule for ideal world.
June 7th	0.16 p.m.	24° N.	New, 1.16 p.m. (5th Perigee).	7.46 a.m., 8.00 p.m.	6.0 & 6.7	−0.1 & 1.0	Lat. and Dec. same name; highest tide follows superior transit agreeably to rule for ideal world.
June 23rd	0.32 a.m.	$26\frac{1}{2}$° S.	Full, 8.12 p.m., 22nd (17th Apogee).	8.46 a.m., 8.44 p.m.	5.2 & 5.8	0.9 & 2.1	Lat. and Dec. contrary names; highest tide after inferior transit agreeing with rule.
July 6th	0.04 p.m.	$26\frac{1}{2}$° N.	New, 9.20 p.m. (3rd Perigee).	7.36 a.m., 7.43 p.m.	5.8 & 6.5	0.1 & 1.4	Lat. and Dec. same name; highest tide follows upper transit agreeably to rule.
December 15th December 17th	11.46 p.m. 0.52 a.m.	26° N.	Full, 11.05 a.m., 15th (15th Perigee).	7.27 a.m., 8.08 p.m.	7.0 & 6.3	1.2 & 0.1	Lat. and Dec. same name; highest tide follows superior transit, according to rule.
December 31st	0.17 p.m.	27° S.	New, 4.21 p.m., 31st	7.06 a.m., 7.54 p.m. ...... 7.46 a.m., 8.32 p.m.	5.9 & 5.4 5.9 & 5.4	2.4 & 1.2	Lat. and Dec. contrary names; highest tide follows inferior transit agreeing with rule.
March 26th....	0.41 a.m.	1° N.	Full, 8.21 p.m., 25th (Apogee).	8.42 a.m., 8.55 p.m.	5.7 & 5.8	1.1 & 1.0	Equinoctial springs; inequality inappreciable.
September 20th	1.03 a.m.	0°	Full, 4.52 a.m., 19th (Perigee).	8.41 a.m., 9.00 p.m.	6.3 & 6.4	0.2 & 0.5	

The mean of the above seven spring tides (five at solstices) gives the highest water 7·7 hours after the moon crosses the meridian required by the rule for the ideal world. Diurnal inequality irregular and greatest at L.W. springs, when it equals $\frac{1}{2}$ to $\frac{3}{4}$, the greatest difference between consecutive springs and neaps, and is about equal to the average. The difference between springs and neaps varies from 0·5 to 2 feet.

DEFINITIONS.

ALTITUDE.—The angular elevation of a body above the horizon, usually expressed in degrees, minutes, etc. At the horizon the altitude is 0°, in the zenith it is 90°.

APHELION.—The point in the orbit of a planet which is farthest from the sun.

APOGEE.—Strictly, the point in an orbit which is farthest from the earth, but the term is now almost exclusively used in connexion with the moon.

AZIMUTH.—The angular distance of a point in the horizon from the North or South point. It is also the angle at the zenith between the meridian of the observer and the vertical circle through the point in the horizon. This vertical circle measures the azimuth of all bodies it passes over.

CIRCLE.—A great circle is one which divides the sphere (celestial or terrestrial) into two equal hemispheres, such as the equator, equinoctial, meridian, and vertical circles. Vertical circles pass through the zenith and nadir, and are perpendicular to the horizon.

CONJUNCTION.—The nearest approach to one another of two heavenly bodies, in contra distinction to "opposition" when they are at the points of greatest separation.

CULMINATION.—The passage of the meridian by a heavenly body. As the meridian is a complete circle the sun crosses it twice daily, and the moon in about 24 hours 50 minutes (lunar day); once above the pole and horizon, and once below the pole and (except in very high latitudes) the horizon. The sun crosses the upper meridian at apparent noon and has its lower culmination at midnight. The moon's meridian passage, transit, or culmination is given in most almanacs and sometimes called southing—a misleading term in all but high N. latitudes.

CYCLE.—A period of time at the expiration of which any aspect of the heavenly bodies recurs, as for instance the Metonic cycle which consists of 19 solar years during which the moon changes 235 times, and the Saros cycle of 18 years and 11 days in which eclipses recur.

DECLINATION.—The angular distance of a heavenly body north or south of the equator. It corresponds to latitude upon the earth.

ECLIPTIC.—A great circle of the Celestial Concave, which indicates the apparent path of the sun amongst the stars and cuts the celestial equator at an angle of 23° 27′.

ELEMENTS.—Data necessary for predicting astronomical phenomena and allied terrestrial ones, such as tides.

ELLIPSOID.—The figure generated by the r volution of an ellipse about one of its axes. e

ELLIPTICITY.—Deviation from circular or spherical form to elliptic or spheroidal. The greater the eccentricity the more elliptic the orbit. The eccentricity is the ratio between the distance from the centre to the focus and the mean distance, or half the axis major of the ellipse.

EQUATOR.—The earth's equator is the great circle midway between the poles. This and every other imaginary circle on the earth is supposed to have its prototype in the celestial concave whose plane is coincident with the terrestrial circle. The celestial equator is called the equinoctial.

EQUINOXES.—The two points where the ecliptic and celestial equator intersect, and so called because when the sun crosses the equator the days and nights are equal all over the world.

HOUR ANGLE.—The angular distance of a heavenly body from the meridian measured at the pole. It can be expressed in hours, minutes, etc., elapsed since the body culminated, or in degrees, minutes, etc., at the rate of 360° to 24 hours, or 1° to 4 minutes.

LATITUDE.—In the heavens the angular distance of a heavenly body from the *ecliptic*. On the earth it is the angular distance from the equator, and this latter corresponds to *declination* in the heavens.

LONGITUDE.—In the heavens an arc of the *ecliptic* intercepted between the great circle through its poles passing over the body and the first point of Aries. On the earth it is an arc of the *equator* intercepted between the meridian of the place and the prime meridian (Greenwich), and corresponds to *right ascension* in the heavens which is measured along the celestial equator and always, like celestial longitude, eastward from the vernal equinox, which is the astronomical prime meridian.

LUNATION.—The period from one change of the moon to the next, viz., 29·5305879 days.

MASS.—The quantity of matter contained in a body, as measured by its weight at a given place. The *mass* is the same everywhere, whereas *weight* differs slightly owing to variations in gravity, which is affected by the shape of the earth and unequal centrifugal force of rotation.

MERIDIANS.—Celestial great circles, infinite in number, passing through both poles and perpendicular to the equator. Each has a corresponding terrestrial meridan passing through both poles, zenith and nadir, and the north and south points of the horizon.

NADIR.—This is the point under our feet to which the plumb line points.

NODE.—The point in which an orbit intersects the ecliptic, ascending if going north, descending if moving south.

OBLIQUITY OF THE ECLIPTIC.—The inclination of its plane to that of the equinoctial or celestial equator and = 23° 27′.

ORBIT.—The path described by a planet round the sun, or by a satellite round its primary, as the moon round the earth.

PARALLAX.—The difference in direction of a heavenly body as seen from two points, as for instance the centre of the earth and some point on its surface. It is evident that this difference will be less the greater the distance of the body. Parallax is used to determine the distance of not too remote celestial objects.

PARALLELS.—Small circles in the heavens and on the earth parallel to the equator.

PERIGEE.—The nearest point of an orbit to the earth, usually applied to the moon.

PERIHELION.—The point of an orbit nearest the sun.

PRIME VERTICAL.—The vertical circle cutting the horizon in east and west points.

QUADRATURE.—The position of the moon when she is 90° from the sun, and therefore in her first and last quarters ; or in the case of an orbit, midway between conjunction and opposition.

SOLSTICES.—The two points of the ecliptic most distant from the equator where the sun attains his greatest declination. With gradually diminishing velocity he here ceases to approach the pole, and after a momentary pause commences with slowly accelerating pace to return towards the equator.

SYNODIC.—This term is applied to movements or periods relative to the sun. A synodical period is the time which elapses between two consecutive returns to conjunction, or opposition.

SYZYGIES.—The points of the moon's orbit in which it is either new or full moon. The line of syzygies passes through these points and crosses the moon's orbit.

TRANSIT.—Passage across a fixed line, as the meridian, or one of the planets across the sun's disc, and the satellites of Jupiter over the disc of the planet.

ZENITH.—The point in the celestial concave to which the vertical line (plumb line) points upward.

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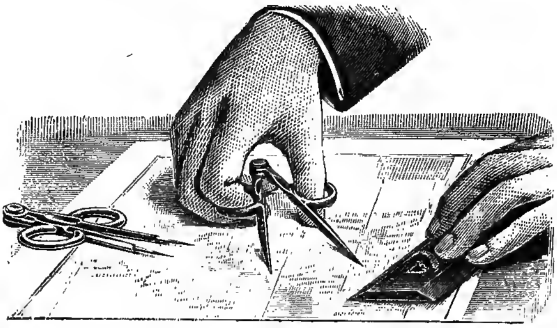

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